PB81-141913

Methodology for Evaluating the Impact and Abatement of Combined Sewer Overflows A Case Study of Onondaga Lake, New York

Stearns and Wheler
Cazenovia, NY

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Nov 80

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/8-80-048	2.	3. RECIPIENT'S ACCESSION NO. PB81 14191 3
4. TITLE AND SUBTITLE METHODOLOGY FOR EVALUATING THE IMPACT AND ABATEMENT OF COMBINED SEWER OVERFLOWS A Case Study of Onondago Lake, New York		5. REPORT DATE November 1980 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Peter E. Moffa, John C. Byron, Steven D. Freedman, John M. Karanik, and Randy Ott		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stearns & Wheler Civil and Sanitary Engineers 10 Albany Street Cazenovia, New York 13035		10. PROGRAM ELEMENT NO. A 35B1C 11. CONTRACT/GRANT NO. R-805096
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U. S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final Report, 6/77 to 10/79 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Richard Field - Telephone (201) 321-6674

16. ABSTRACT

A general methodology is presented for the evaluation of the impact and abatement of combined sewer overflows on receiving waters. It was developed from experience with Onondaga Lake, an urban lake in central New York that receives combined sewer overflows from the City of Syracuse via three tributary streams.

Field measurements were made of representative combined sewer overflows and the receiving water for the purpose of developing individual mathematical models. These models were employed to project the magnitude of pollutant load from a combined sewer system for different storm conditions and the associated receiving water impact, respectively. The results of these two models can be combined to express the abatement cost to achieve different water quality standards.

A maximum DO deficit of 2.8 mg/l in Onondaga Lake was predicted for a 10-year storm. Bacterial violations can occur as many as 38 times during an average rainfall year. Abatement beyond the "cost-effective" point will be necessary to assure the lake's use for contact recreation.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Water pollution, combined sewers, water quality, wastewater, methodology, mathematical models, cost-effectiveness	Lakes, receiving water impacts, combined sewer overflows, facility planning	13B

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE:1980--757-064/0177

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/8-80-048
November 1980

PB81-141913

Research and Development

EPA

User's Guide

Methodology for Evaluating the Impact and Abatement of Combined Sewer Overflows

A Case Study of Onondaga Lake, New York

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the "SPECIAL" REPORTS series. This series is reserved for reports targeted to meet the technical information needs of specific user groups. The series includes problem-oriented reports, research application reports, and executive summary documents. Examples include state-of-the-art analyses, technology assessments, design manuals, user manuals, and reports on the results of major research and development efforts.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/8-80-048
November 1980

METHODOLOGY FOR EVALUATING THE IMPACT AND ABATEMENT OF COMBINED SEWER OVERFLOWS

A Case Study of Onondaga Lake, New York

by

Peter E. Moffa
John C. Byron
Steven D. Freedman
Stearns & Wheler, Civil and Sanitary Engineers
Cazenovia, New York 13035

and

John M. Karanik
Randy Ott
Department of Drainage and Sanitation
Onondaga County, New York 13215

Grant No. R805096

Project Officer

Richard Field
Storm and Combined Sewer Section
Wastewater Research Division
Municipal Environmental Research Laboratory (Cincinnati)
Edison, New Jersey 08817

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

i.a

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This Methodology can be used by municipalities, consulting engineers and planners for the evaluation of the impact and abatement of combined sewer overflows on receiving waters. In this report the relationships between rainfall and overflow and between overflow and water quality are developed and an approach for selection of the most cost-effective level of treatment is presented.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

A general methodology is presented for the evaluation of the impact and abatement of combined sewer overflows on receiving waters. It was developed from experience with Onondaga Lake, an urban lake in Central New York that receives combined sewer overflows from the City of Syracuse via three tributary streams.

Field investigations of the combined sewer system and the receiving water must first be undertaken. The field work includes flow measurement and water-quality sampling of the sewer overflows and the receiving water during several different storms. Use of a computerized data bank has been found virtually essential for the storage and manipulation of the large quantity of data resulting from the sampling and analysis.

Mathematical modeling of the receiving water is undertaken to evaluate water quality as a function of pollutant load; the storm sewer system is modeled to determine the quantities of pollutants discharged during various storm conditions. Prior to the modeling effort, analysis of local rainfall records is necessary to develop the classical intensity-duration-frequency relationships. After assessing the water-quality impact of dry-weather pollutants from wastewater treatment plants and other sources, the results of the two models can be combined to express the reduction in stormwater pollutants needed to achieve a particular water-quality goal as a function of storm frequency or storm recurrence interval.

Abatement alternatives, and their respective costs, for the reduction of pollutants from wet-weather sources, particularly combined sewer overflows, are next investigated. Using engineering judgment of the most effective and economic abatement measures, a relationship is then developed between abatement cost and storm condition for each of several water-quality criteria or goals. From the cost-benefit relationships thus developed, a graphical determination can be made of the "general optimum solution" (GOS) for reduction or treatment of combined sewer overflows.

It is recognized that the quality of the receiving water resulting from the GOS may not be acceptable to the general public or regulatory agencies. In that case, a decision to provide greater (or lesser) pollution abatement

will be based upon social or political considerations, but the governmental body making the decision will be cognizant of its economic implications.

In the study for Onondaga County, New York, from which the methodology was developed, 35 overflows from the combined sewers of the City of Syracuse, which serve an area of about eight square miles, were monitored for a period of one year. Onondaga Lake, the principal receiving water, is approximately four and one-half square miles in surface area; it was sampled at ten surface locations, each at two distinct depths, for the period of influence of each of six storms. The Storm Water Management Model (SWMM) was applied to the City's sewer system. A 27-segment, three-dimensional, dynamic water-quality model of the lake, with capability of predicting enteric bacteria, dissolved oxygen, nutrients, and toxic materials, was developed.

From the models, it was determined that the impact of CSO's on dissolved-oxygen concentrations in Onondaga Lake will not be critical after tertiary treatment facilities for dry-weather wastewaters are placed in operation; a maximum DO deficit of 2.8 milligrams per liter was predicted for a 10-year, two-hour storm. Combined sewer overflow contributions of phosphorus will be negligible in comparison to those from other sources.

In an average rainfall year, 38 violations of the fecal coliform standard will occur in the area of the lake intended for contact recreation. If abatement of CSO pollution were to follow the "general optimum solution" of this methodology, there would still be 13 annual violations, ten of which would occur from June through September. Inasmuch as each violation persists for about three days, more extensive CSO abatement will be required if the projected recreational usage of Onondaga Lake is to be realized.

This report was prepared in fulfillment of Grant No. R805096 by Stearns & Wheler, Civil and Sanitary Engineers, and the Onondaga County Department of Drainage and Sanitation, under sponsorship of the U.S. Environmental Protection Agency.

CONTENTS

Foreword iii
Abstract iv
Figures x
Tables xiii
Acknowledgments xv

1. Introduction 1
2. Summary 3
    - Combined Sewer Overflow System 3
        - Onondaga County 4
    - Receiving Water Sampling 5
        - Onondaga County 6
    - Data Bank 6
        - Onondaga County 7
    - Mathematical Modeling of Combined Sewer System 7
        - Onondaga County 8
    - Mathematical Modeling of Receiving Water 8
        - Onondaga County 9
    - Model Projections 10
        - Onondaga County 10
    - Cost-Effectiveness Analyses 11
        - Onondaga County 12
3. Recommendations 14
4. Combined Sewer Overflow System 15
    - Selection of CSO Monitoring Sites 15
        - Onondaga County 16
    - Equipment Installation 16
    - Overflow Sampling Program 22
        - Flow Monitoring 22
            - Onondaga County 23
        - Quality Sampling 23
            - Parameters 23
            - Location 25
            - Duration 25
            - Frequency 25
            - Automation 26
            - Manual Sampling 26

CONTENTS (continued)

5. Receiving Water Sampling 27
    General 27
    Water Quality Concerns 28
    Sampling Locations 31
    Duration of Sampling 33
    Frequency of Sampling 33
    Automation 35
6. Data Bank 36
    Onondaga Lake 38
7. Mathematical Modeling of Combined Sewer System 39
    Objective of Modeling 39
    Types of Models Available 40
        Levels of Analysis 40
        EPA SWMM 42
        EPA Simplified SWMM (SSWMM) 43
            Rainfall Characterization 44
            Storage-Treatment Balance 45
            Overflow Quality Assessment 45
            Receiving Water Response 45
        Comparison of Detailed Single-Event SWMM and Simplified SWMM (SSWMM) 45
        Complementary Model Usage 45
    Design Considerations for Quantity Projections 47
        Continuous Simulation 47
        Single-Event Design Storm 48
        Other Techniques 50
    Design Considerations for Quality Projections 50
        Pollutant Characteristics 52
    CSO Modeling for Onondaga County 53
8. Mathematical Modeling of Receiving Water 59
    Preliminary Approach 59
        Onondaga County 63
    Detailed Model 64
        Fecal Coliform Model Kinetics 67
        Total Phosphorus Model Kinetics 68
        Dissolved Oxygen Model Kinetics 69
            Removal Rates for Organic Components 69
            Biological Deoxygenation 70
            Benthal Oxygen Demand 71
            Reaeration 71
            Temperature Corrections 73
            Net Productivity 73

CONTENTS (continued)

Model Calibration and Verification 75
Hydrology, Influent Loads, Circulation, Dispersive Transport 75
Reaction Coefficients 76
Environmental Conditions 79
Sensitivity Analysis 79
9. Model Projections 90
Critical Input Conditions 90
Onondaga County 94
Projected Pollutant Load 95
Onondaga County 97
Lake Model Projections 98
Results - Onondaga Lake 98
10. Cost-Effectiveness Analysis 104
CSO Relationships 104
Rainfall Patterns 104
Receiving Water Impact 106
CSO Discharges 106
Abatement Costs 108
Cost-Effective Solution 110
Onondaga County 112

References 117

FIGURES

Number		Page
1	Typical control section and flow monitoring structure	17
2	CSO modeling tasks and data requirements	18
3	Typical layout of combined sewer system at the point of overflow	19
4	Plots typical of CSO data presentation	21
5	Relationship between accuracy of measured runoff coefficient and number of storms monitored	24
6	General plan and sampling locations for Onondaga Lake	32
7	Model segmentation	34
8	Summary of data review process	37
9	Major components of EPA Storm Water Management Model	42
10	Interrelationship of tasks in the Simplified Stormwater Management Model	44
11	Synthetic hyetograph for Syracuse, New York	49
12	Typical correlation between total rainfall and total overflow for an individual drainage area	54
13	Comparison of SWMM and SSWMM output to measured data for Onondaga County, New York	55
14	Total BOD_5 load discharged from the combined sewer system to Onondaga Creek for storms of various return periods	58

FIGURES (continued)

Number		Page
15	Time frame of concern for various water-quality parameters	60
16	Development of predictive water quality model	61
17	Comparison of the effects on concentration of advective and advective - dispersive transport	65
18	Forces acting on a pollutant mass discharged to a two-dimensional advective - dispersive system	66
19	Reaeration rate as a function of wind speed	72
20	Individual current measurements	76
21	Development of calibrated fecal coliform model	80
22	Development of calibrated dissolved-oxygen model	81
23	Comparison of measured fecal coliform concentrations with model output	82
24	Comparison of measured CBOD concentrations with model output	83
25	Comparison of measured NBOD concentrations with model output	84
26	Comparison of measured DO concentrations with model output	85
27	Comparison of measured Total Phosphorus concentration with model output	86
28	A typical loading curve relating pollutant load to water quality response	91
29	General procedure for developing loading curve and determining allowable load	92
30	Fecal coliform loading curves for Onondaga Lake	102

FIGURES (continued)

Number Page

31 Summary of monthly rainfall data 105

32 Intensity-duration-frequency curves, Syracuse, New York... 107

33 Procedure for establishing the most cost effective treatment level to meet a given water quality goal....... 109

34 Procedure for determining the cost effective water quality goal 111

35 Number of water quality violations occurring annually in Onondaga Lake as a result of treating various intensity storms 113

36 Costs associated with treatment of combined sewer overflows to reduce the frequency of annual water-quality violations 114

37 Average number of violations of fecal coliform standards during the recreation season resulting from treating various intensity storms, Onondaga Lake, New York 116

TABLES

Number		Page
1	Water Quality Parameters	30
2	Categories of Stormwater Models	40
3	Stormwater Analysis Level and Model Complexity	41
4	Comparison of Single-Event SWMM and SSWMM	46
5	Factors Affecting CSO Quality	51
6	Geometric Mean Concentrations of Pollutants Entering Onondaga Creek and Ley Creek from Combined Sewer Overflows	57
7	Temperature Correction Factors	73
8	Dispersion Coefficients	77
9	Reaction Coefficients and Sinking Rates Verified Through Model Calibration	78
10	Dissolved Oxygen Reaction Coefficients	78
11	Sensitivity Analysis, Reaction Rates	88
12	Sensitivity Analysis of Productivity on In-Lake Dissolved Oxygen	89
13	Critical Environmental Conditions for Model Projections	93
14	Dry-Weather Pollutant Loads	99
15	Wet-Weather Pollutant Loads	100

TABLES (continued)

Number / Page

16 Projected Impact of Wet-Weather Loads on Onondaga Lake 101

17 Average Annual Phosphorus Concentrations in Onondaga Lake 103

ACKNOWLEDGMENTS

John M. Karanik, Deputy Commissioner, and Randy Ott, Project Engineer, for the Onondaga County Department of Drainage and Sanitation served effectively to coordinate the related projects performed by O'Brien & Gere and Stearns & Wheler. Facilities planning and previous EPA demonstration projects conducted through Onondaga County, New York, served as the primary basis for this methodology.

O'Brien & Gere Engineers, Inc., is presently conducting facilities planning for the combined sewer overflow system. The cooperation of a number of engineers, and in particular, Mr. Dwight MacArthur, Managing Engineer, and Mr. Thomas Jordan, Project Engineer, of O'Brien & Gere, is gratefully acknowledged.

Stearns & Wheler conducted the receiving water investigations as part of this facilities planning. Dr. Raymond P. Canale, President, and Mr. Paul Freedman, Vice President, of Limno-Tech, Inc., developed much of the receiving water modeling.

Project Officer Richard Field and Messrs. Rick Traver and Douglas Ammon of EPA provided guidance and review throughout the project.

Dr. William O. Lynch of Stearns & Wheler, who was the partner in charge, closely reviewed this report and offered many valuable suggestions.

SECTION 1

INTRODUCTION

The impetus provided by the Federal laws concerning water pollution (1, 2) has resulted in great strides in wastewater treatment. The prevailing attitude leading to the 1972 Amendments to the Water Pollution Control Act (1) was that there had been a general lack of progress in abating the country's pollution. Consequently, secondary treatment plants throughout the country were approved and initiated on the basis of the obvious benefit to receiving water quality. The latter benefit was provided through water quality impact studies as part of Section 201 of PL 92-500.

However, since 1972, the required "201" facilities planning has progressively expanded to include analyses and evaluations of separate sewer systems, and most recently, combined sewer systems. The combined sewer overflow (CSO) investigations have had to address an old but relatively undefined component of municipal sewage; namely, stormwater. The highly variable nature of this element and its double-edged impact on receiving water of providing dilution as well as adding pollutants has resulted in a more deliberate approach to cost-benefit relationships than had previously been the case for "201" facilities planning.

The common "dry weather" receiving water standard based on consecutive seven-day low flow conditions (MA7CD10) occurring once every ten years for conventional treatment has gradually given way to the consideration of allowing deviation from "dry weather" for certain stormwater events. Recently, attention has been devoted to the concept of the "design storm" as being that storm for which abatement facilities are planned (3). However, the elusiveness of this approach has led to the consideration of cumulative storm effects over annual cycles. A defined approach is not yet available, but actual ongoing experiences are now providing the basis for practical approaches to the problem.

The methodology outlined herein is based largely on the successful experience in identifying the discharges from a combined sewer system and their impact on the water quality of an urban lake on Onondaga County and just north of Syracuse, New York. This methodology is not limited to

Onondaga County, but draws from other experiences as well and to a large extent is applicable to receiving waters in general.

The methodology is broken down separately for both the combined sewer system and the receiving water aspects into. (a) equipment installation; (b) field sampling; (c) data analyses and mathematical modeling; and (d) impact projections. The extent to which sewer system investigations are related to receiving water investigations and the coordination required to arrive at an overall abatement strategy will be described.

SECTION 2

SUMMARY

The experiences of Onondaga County, New York, in defining the pollutants discharged from the City of Syracuse's combined sewer system and their impact on the water quality of Onondaga Lake served as the basis for developing a general methodology applicable to other communities. Combined sewer overflow (CSO) investigations were conducted by one firm of consulting engineers, while receiving water investigations were conducted by a second firm; both efforts were funded under a PL 92-500 Facilities "201" Grant to Onondaga County for the Syracuse Metropolitan Sewage Treatment Plant.

In the summary that follows, each major topic is initially discussed in broad, general terms, then illustrated by specific reference to the procedure followed in Onondaga County.

COMBINED SEWER OVERFLOW SYSTEM

The first step in a CSO study is to identify the pollutants through field sampling and laboratory analysis of overflows at selected sampling sites. The number and location of sampling sites should be based on the extent to which they represent the system as a whole. Resulting data can then be projected to portray the entire system. Other practical considerations should be taken into account, such as accessibility of manholes and the hydraulic characteristics of the various structures in relation to accuracy of flow measurement.

Local rainfall data and the physical characteristics of the sewer system are analyzed and used to develop a series of mathematical relationships that express the operation of the system under various rainfall conditions. The number and location of rain gages is important to being able to relate the rainfall in a particular area to its associated runoff. As a general rule, a density of one to five rain gages per square mile is desirable. Care should be exercised in locating these gages so as to minimize any interference from nearby structures or trees.

The measurement of quantity at an overflow may involve the measurement of the flow reaching the interceptor as well as the flow discharged to the receiving water, depending upon the capacity of the interceptor. The number of individual points that have to be measured should be minimized to reduce equipment maintenance and data coordination. It also is desirable to install the flow metering device at the same location as the automatic sampler which measures quality so that operation of the sampler will be triggered by an actual overflow occurrence. Such time coordination becomes critical for determining pollutant loads, which are calculated as the product of flow quantity and pollutant concentration. Thus, the simplest and most direct measurement is at the overflow to a receiving water. Under surcharge conditions, it is particularly necessary to estimate the interceptor flow as well as the receiving water overflow in order to determine the true quantity of runoff originating from a tributary area.

The quality parameters selected for a monitoring program are dependent upon the intended best usage of the receiving water. The frequency and duration of sampling should be based on an adequate description of the peak period of pollutant discharge, often called the first-flush period, and the subsequent subsidence of this period to relatively insignificant quantities. It has been found that in the period of five minutes following the onset of runoff, significant concentrations of pollutants can occur. Thereafter, 7-minute intervals have proven to be adequate to define an overflow discharge. In general, the minimum duration of sampling should be ample to capture the runoff from a six-hour storm.

Onondaga County

The combined sewer system of the City of Syracuse covers approximately eight square miles and has 87 active overflow sites, of which 35 were monitored for flow quantity and pollutant quality. The monitored sites encompassed 85 percent of the total defined runoff area and hence were representative of the overall system. To monitor rainfall, six rain gages were located throughout the City, each representing an area of approxmately two square miles.

The main interceptor system has little or no capacity for wet-weather flow and thus the quantity of flow discharged to the stream was assumed to be the total quantity entering the diversion structure. This assumption may not be applicable in many cases and must be verified by field data.

Overflows were monitored through the use of ultra-sonic flow meters in combination with sampling units capable of taking 24 separate samples. Samplers were initiated by a signal from the flow meter and were operated at 7-1/2-minute intervals thereafter.

RECEIVING WATER SAMPLING

Adequate information on receiving water quality is generally lacking. Such information is probably more critical for CSO projects than for conventional wastewater treatment because water-quality impact is more difficult to predict and the risk of providing unneeded abatement facilities is greater.

Although combined sewer overflows can introduce a multitude of pollutants into a receiving water, the primary concerns can be categorized into (a) pathogens, because of public health, and (b) dissolved oxygen, nutrients and toxics, all because of their direct effect on the aquatic system and indirect effect on public health. The fecal coliform and fecal streptococcus groups can be used as pathogenic indicators. Dissolved oxygen, phosphorus, and, in some cases, nitrogen, are critical nutrients or indices to be evaluated for their impact on aquatic life. Initially, evaluation of toxics should be limited to the heavy metals, unless specific information indicates the need to investigate toxicity from organic chemicals, e.g., pesticides, PCB's. Organic analyses represent a relatively high level of complexity. Toxicity observed in the BOD test can be used as an indicator for proceeding with any additional analyses. One exception to this dictum would be the case where bottom deposits that may be subject to toxic organic contaminants are scoured frequently and play a significant role in the year-round quality of overlying waters.

Decisions as to what storms should trigger receiving water sampling should be based on the anticipated storm intensity. Close coordination should be maintained with those sampling the sewer system so as to maximize the number of overflows being monitored during receiving water sampling. Sampling locations and the frequency and duration of sampling are dependent upon the changes a particular parameter may undergo during a storm period. Thus, prior knowledge from other studies or background data on the receiving water is helpful. In the absence of such information, the general guidelines outlined herein can be used.

The location of sampling points should reflect the intended usage within the body of the receiving water. In general, areas where contact recreation is anticipated should be sampled more intensely than areas where fishing or boating are anticipated. The circulation pattern of the receiving water should be considered in determining surface locations and depths of sampling. Surface locations should include tributaries before entering the lake as well as in-lake locations reflecting the outer boundary of any such tributary's mixing zone. In this way, the impact of a particular tributary can be estimated. If a tributary receives combined sewer overflows, it should be sampled so as to bracket these discharges, either individually or collectively.

Onondaga County

Water-quality data from dry-weather periods were available for Onondaga Lake and were used to estimate the pollutant levels expected during storms. In actuality, these estimated levels were often exceeded.

Anticipated storm intensity determined whether or not receiving water sampling was to be conducted for any particular storm. On each positive occasion, the crews in charge of sampling the sewer system were alerted. The frequency and duration of sampling during a storm were estimated at the onset of the project, but were later adjusted on the basis of the first two storms. The water-quality parameters generally measured were bacteria, BOD, DO, solids, nutrients, and heavy metals.

All major tributaries were sampled and measured at their points of entrance into Onondaga Lake. In addition, two of the tributaries were sampled upstream so as to bracket the collective input of the combined sewer system. Preliminary sampling was performed to determine the validity of sampling techniques for each of the tributary locations. To be representative, tributaries were sampled in cross section and in depth, depending upon their dimensions and the degree of mixing in each. The lake was sampled at ten surface stations; each station was sampled at two depths to reflect the epilimnetic (upper) and hypolimnetic (lower) waters. One surface station was located at each of the lake's two deepest points, the remainder being located to reflect tributary inputs or shoreline areas expected to be used for contact recreation.

DATA BANK

Whenever CSO studies yield large amounts of data, it is important that they be handled in a form that is easily retrieved and analyzed. For any kind of system, every sample must be adequately identified, e.g., storm number, location, date, time and parameter. A data file may take the form of summary sheets or can be computerized, depending upon the size of the project. A computerized file will permit the rapid retrieval of data in various forms, which is particularly helpful in CSO projects where dilution volumes of samples for certain parameters may have to be adjusted following the first storm sampling. These and other adjustments, such as monitoring locations and possible elimination of certain stations, require that initial data be evaluated as soon as possible. Provision should be made to plot the concentration levels of the various parameters versus time for a given combined sewer overflow and, when combined with flow, calculate a plot of pounds of material versus time. Other sub-routines could be developed to determine the pounds of material discharged during an entire storm.

Onondaga County

A computerized file system was established for the combined sewer system and a separate file was set up for the receiving water. Since the combined sewer system investigation and the receiving water investigations were conducted by independent organizations, separate data systems were developed; this presented no problem since, with the exception of storm sampling, the data analyses were relatively independent of each other. The output requirements and mathematical modeling for the sewer system were markedly different from those of the receiving water.

MATHEMATICAL MODELING OF COMBINED SEWER SYSTEM

The complexity of combined sewer systems and the variety of use of tributary lands generally requires a series of mathematical expressions or a mathematical model to project the pollutant discharges associated with various storm conditions. There are no guidelines for the storm conditions for which abatement facilities should be designed. Only on the basis of actual field measurements and the subsequent development of cost-benefit relationships can reasonable design decisions be made. The capturing of storm conditions for which facilities should be designed would be pure happenchance; therefore, mathematical modeling of the sewer system as well as the receiving water becomes an integral part of a CSO study.

The major objective of a field sampling program is to measure actual discharges and their impact on water quality sufficiently to develop the cause-and-effect relationships between the sewer system and the receiving water. A mathematical model can then be developed to describe these relationships and used to project combined sewer overflows for various storm conditions. There are a number of mathematical models available to perform this service, depending on the complexity of the combined sewer system. In some cases, preliminary simplified modeling should be performed to establish guidelines for the application of more extensive modeling. Simplified modeling can be particularly useful in estimating the long-term rainfall picture or performing continuous simulation, whereas more detailed modeling is required for single-storm evaluations.

A major limitation of the models that are available is the level of accuracy with which they predict pollutant concentrations. The use of statistical analyses of quality data to develop coefficients for use in conjunction with quantity data has been an approach. Thus, mathematical models can be used to estimate CSO quantities and statistical analyses can be used to associate quality with the models' outputs.

Onondaga County

The Simplified Stormwater Management Model (SSWMM) was used to estimate the total volume of overflow from the Syracuse system for various rainfall conditions so that preliminary storage and treatment schemes could be developed and screened. The SSWMM was calibrated against 35 actual overflow points; however, surcharge conditions, which existed in all but very minor storms, limited application of the simplified model. Accordingly, the CSO system was modeled using the detailed Storm Water Management Model (SWMM) with the EXTRAN option, which provides the means for calculating surcharge conditions. Data from the individual overflows were also used to calibrate the detailed SWMM.

For the purpose of defining rainfall conditions, a statistically random two-year data set of the rainfall record for the Syracuse area was developed and found to be equivalent to the 25 years of record available. The two-year record was then used to develop rainfall hyetographs representing various recurrence intervals. Pollutant loadings were determined by combining statistical analysis of the field-measured quality parameters with associated flows. Quantity and quality responses were simulated for a number of storm conditions. The pollutant loadings were then entered in the receiving water model to assess water-quality impact.

MATHEMATICAL MODELING OF RECEIVING WATER

Because of the great range and variability of weather patterns, combined sewer system characteristics, and receiving water usage, it is unlikely that any pre-determined criteria of receiving water quality, quantity and recurrence interval can be as universally adopted to set the treatment of CSO pollutants as they have been adopted to set the treatment of dry-weather pollutants in conventional plants. Consequently, it is necessary and desirable to develop the relationships required to determine the water quality impact of CSO's under a variety of conditions. Mathematical modeling of the receiving water greatly facilitates this need. The type of model employed is dependent on intended best usage of the receiving water, time frame, confidence level, and project scope. Simplified modeling should be attempted initially to determine if more detailed modeling is needed. If the results of the simplified approach border on contravention or violation of some established standard, then more detailed modeling is warranted.

A receiving water model should include certain fundamental functions as well as those required to meet specific needs. The model should consider circulation as fundamental to the distribution of pollutants in the receiving water. The circulation model should include advective and dispersive transport and, in addition, mechanisms for settling and scour. The modeling of pollutants can be done in a modular fashion to minimize computer costs and, in general, should include (1) bacteria, (2) DO balance, (3) nutrients, and (4) distribution of conservative materials, e.g., heavy metals.

The success of a mathematical model is the degree to which it represents real conditions; hence, the receiving water model should be calibrated against several storms and verified accordingly. If a number of constants were employed in the model because of practical limitations in the office or conditions experienced in the field, these values can be tested through sensitivity analyses. Through such analyses, the concern for assumed values can often be minimized.

Onondaga County

Simplified modeling of a one-year storm showed contravention of bacterial standards throughout the recreational zones of Onondaga Lake. In order to verify these results, more detailed modeling was undertaken. Simplified modeling was attempted to determine the dissolved-oxygen relationships in the lake; owing to the complexity and intensity of algal growths and their significant influence on the DO level, a more detailed model was required. A simplified approach, on an annual basis, was taken to determine the significance of phosphorus loadings from storm runoff. This approximation was considered adequate to assess what turned out to be the relatively insignificant contribution of stormwater to the phosphorus content of the lake.

Each CSO was identified as entering one of two tributaries to the lake. In the detailed receiving water model, the CSO's entering each tributary were treated as single, collective inputs. The lake was divided into 27 distinct segments for the purpose of defining circulation patterns. Twenty-one (21) of the segments were located in the epilimnetic (upper) waters and six of the segments were located in the hypolimnetic (bottom) waters. The model utilized steady-state circulation patterns and hydraulic loads in combination with time-variable pollutant loads to simulate the lake's water-quality response to stormwater discharges. Bacterial modeling was undertaken specifically for fecal coliforms and accounted for loss of organisms due to both settling and die-off, including terms for protozoan predation and sunlight disinfection as well as respiration and natural death. The dissolved-oxygen function included expressions for algal photosynthesis and respiration. Total phosphorus was considered to be a relatively conservative substance in which net changes in concentration were limited to settling and sediment release.

The Onondaga Lake model was calibrated with data from four distinct storms. The resulting model was then used to predict two of the same storms and, in both cases, resulted in good fits. In addition, sensitivity analyses were performed for the various rate coefficients. In general, 25 to 50 percent changes, plus and minus, in the coefficients originally employed were used to test the model's sensitivity to such values in terms of water-quality impact.

MODEL PROJECTIONS

Prior to projecting abatement requirements, the critical environmental conditions must be determined for use in the water-quality model. These conditions include wind speed, background water quality, light conditions, and temperature. Input conditions must be carefully selected so as to be critical for the parameter in question. For example, the effect of fecal coliforms on water quality is most severe under conditions of minimal die-off (low temperatures) and rapid transport (high wind speeds) to a sensitive area of a lake, such as a bathing beach; the dissolved oxygen parameter, on the other hand, is most adversely affected when biochemical rates are maximum (high temperatures) and reaeration is minimum (low wind speeds). Since historical records generally are not available for lake circulation patterns, the flows used in the predictive water-quality model must be determined through lake current measurements in conjunction with recordings of wind speed and direction. Bacterial die-off rates should be determined through laboratory-controlled tests on the receiving water. In predicting the dissolved-oxygen content of productive lakes, light conditions and the algal standing crop can represent the dominant effect on the DO concentration.

The projection of pollutant loads requires considerable judgment to avoid a combination of events that may have a very infrequent reoccurrence interval. If, for example, an MA7CD10 dry-weather stream flow is combined with storm runoff having a recurrence interval of one year, the probability of both conditions occurring at the same time can exceed once in 30 years. The selection of dry-weather flow conditions for a large lake is less critical than for a stream because circulation is more influenced by lake elevations and lunar effects than incoming tributaries. In addition to flow considerations, pollutant loadings in a model must include dry-weather components representing both point and background sources. Point source information often can be obtained through the NPDES or State permit system, but background source information may require field measurements during dry periods.

Onondaga County

Current measurements taken on Onondaga Lake during the storm sampling periods served as the basis for determining the in-lake circulation patterns assumed in the mathematical model. Background water-quality data was available from prior dry-weather sampling. Light conditions were determined from regional data in conjunction with percent-cloud-cover measurements at the local weather station.

Dry-weather data from prior years served as the basis for determining point-source pollutants. The data used were limited to the months of June through September and represented average values of two to six years of data, depending upon whether or not the data reflected contemporary operations in the tributary. In some cases, modification of the sewer system prevented the use of all six years of data.

Projections of the water-quality impact of storms with recurrence intervals of one (1), two (2) and ten (10) years were made. It was found that the one-year, two-hour storm would result in bacterial numbers in excess of the standard of 200 cells/100ml in all "upper" segments of the lake, and a maximum concentration of greater than 11,000 fecal coliform cells/100ml in the northern basin where contact recreation is anticipated. It was predicted that a storm of this magnitude would cause contravention of coliform standards for a period in excess of three days. On the other hand, the dissolved oxygen demand from even a 10-year, two-hour storm had only minimal effect on the dissolved-oxygen balance of the lake; the maximum DO deficit for that storm, under the most critical conditions, was determined to be 2.8 mg/l. It was determined that the algal standing crop and abrupt algal die-off, following treatment of the domestic and industrial wastes, will become the principal factor affecting the lake's dissolved oxygen. Annual storm-related contributions of total phosphorus are negligible when compared to the projected dry-weather loads.

COST-EFFECTIVENESS ANALYSES

A common economic approach to stormwater treatment has been to develop relationships between the impact of stormwater on receiving water quality and the cost of treatment for various storm conditions. This cost-benefit information has then been used by local governments and regulatory agencies to make reasonable economic decisions.

Through the use of a receiving water model, water quality response can be expressed as a function of total pollutant load, including both dry-weather loads and stormwater inputs, especially CSO's. An independent combined sewer system model can be used to relate the pollutant load discharged to various storm conditions which can be expressed in terms of recurrence interval. If the receiving water can assimilate the dry-weather component of the pollutant load after suitable treatment, the two relationships previously developed can be combined to express the required removal of pollutants from the wet-weather components, for any water-quality goal, as a function of storm recurrence interval.

A series of cost estimates must then be prepared for the removal of various quantities of pollutants from the combined sewer system, using engineering judgment as to the best method of accomplishing each level of abatement. Abatement can be classified as either source control or treatment. Source controls or "best management practices" (BMP) include control before the stormwater enters the combined sewer system or control within the sewer system itself. Treatment of combined sewer overflows can take place either at the individual diversion chambers within the systen or at one or more locations along each interceptor.

The abatement costs can then be combined with the previously developed relationships between required pollutant removal and storm condition to yield a graphical presentation of the cost of meeting a particular water-quality goal versus storm recurrence interval or a measureable benefit such as number of water-quality violations. Rainfall records can be employed to determine the frequency of violation over the period of record available. The plotted curve of this relationship may show a pronounced "knee"; this knee may be interpreted as representing the highest recurrence interval (lowest storm frequency) or least number of water-quality violations at which a water-quality goal can be met at a relatively low marginal cost. It is the optimal or cost-effective solution for that particular water-quality standard. At all points beyond the knee (the point of "diminishing returns"), the additional benefits derived from incremental increases in expenditure decrease rapidly and can be justified only for reasons other than economic ones.

Similar curves can be developed for different water-quality standards and the entire family of such curves analyzed to weigh the merits of more stringent or less stringent standards. In the absence of national guidelines and in consideration of the many and varied factors involved in stormwater abatement, economic relationships such as those just described become essential to the formulation of reasonable plans for the abatement of pollution from stormwaters, especially combined sewer overflows.

Onondaga County

Analysis of the Onondaga Lake data showed that only the fecal coliform parameter was significantly and adversely affected by CSO discharges. Of the 65 annual overflow-producing events, 38 result in discharges of significant magnitude to cause violation of the bacterial standards in the contact recreation zone.

For a maximum bacterial concentration (or standard) of 200 cells/100 ml, various abatement alternatives were plotted against the number of violations of this standard that would occur in the lake in a typical rainfall year. The "knee" of the curve occurred at a point where there would still be 13 annual violations, ten of which would occur during the recreation season from June through September. Since ten violations would essentially close the lake to contact recreation, higher levels of pollution abatement are now being considered, the goal being a maximum of one violation.

SECTION 3

RECOMMENDATIONS

On the basis of the experiences of Onondaga County, the following recommendations are made for communities facing similar problems of evaluating and abating pollution from combined sewer overflows:

1. The water-quality impact of the combined sewer overflows should be determined by measurement and analysis of representative overflows and the receiving water under real storm conditions.

2. Mathematical relationships should be developed from these data for the purpose of projecting the impact of overflows on water quality under a wide range of storm conditions.

3. Costs should be developed for abatement plans representative of a range of water-quality goals associated with various storm conditions.

4. Cost-benefit relationships should serve as the basis for selecting the water-quality goals, associated stormwater conditions, and abatement methods that best fit both the local needs and the national interest.

SECTION 4

COMBINED SEWER OVERFLOW SYSTEM

Prior to evaluating the impact of the overflows on the water quality of a receiving water, the pollutional load contributed from this source must be identified. Since for most communities it is financially and physically impractical to monitor all overflow sites, it is necessary to select for monitoring some representative locations with drainage basin characteristics similar to the unmonitored areas. The observed characteristics may then be applied to the unmonitored areas for projecting overflow quantities.

SELECTION OF CSO MONITORING SITES

Major factors to be considered in the selection of monitoring stations are size of drainage area, uniformity of land uses within that drainage area, slope and percent imperviousness of the land, and overall applicability of the particular drainage basin characteristics to other areas within the system.

The preliminary selection of these sites can be made with the aid of detailed sewer maps, land use maps, aerial photographs and topographic maps, in conjunction with physical inspection. This type of information is generally available for most cities throughout the country. Once an adequate number of sites have been selected by "desk-top" studies, it becomes necessary to use field investigations to verify the appropriateness and ease of monitoring of these sites.

The ability to utilize a selected site is dependent on accessibility, the hydraulic condition at the point of flow measurement, and the slope within the contiguous transport system. Since samples will be collected during inclement weather, the accessibility of the site is extremely important, primarily from a safety standpoint. The hydraulic condition at the point of measurement is critical to accurate flow measurement and will determine the method of measurement employed. The accurate measurement of flow requires the use of a control section for which a relationship between head and flow exists (3). This often requires installation of a control section, such as a weir. The need for such construction may severely reduce the number of suitable monitoring sites.

Weirs, when used, should be constructed as high above the invert of the incoming sewer as possible (Figure 1) in order to minimize the approach velocity at the point of measurement. This minimizes the velocity head, which enables the use of simplified weir formulas which require only a measure of depth of flow over the weir (H) to calculate flow. Elevating the weir crest also decreases the chances of weir submergence ($h_d > h_w$); however, it increases the chances of basement flooding upstream of the weir. Prior to altering the hydraulics, the slope of the upstream sewer system should be checked to insure that it is sufficient to permit this construction without risking severe backup.

An alternate to the construction of a control section is to utilize the sewer pipe itself as a control section and monitor flow either in the pipe upstream of the diversion (total flow) or in the outfall pipe itself (overflow). No matter where monitoring is accomplished, the selected structure or manhole must also be of sufficient size and depth to permit installation of monitoring equipment if costs are to be minimized.

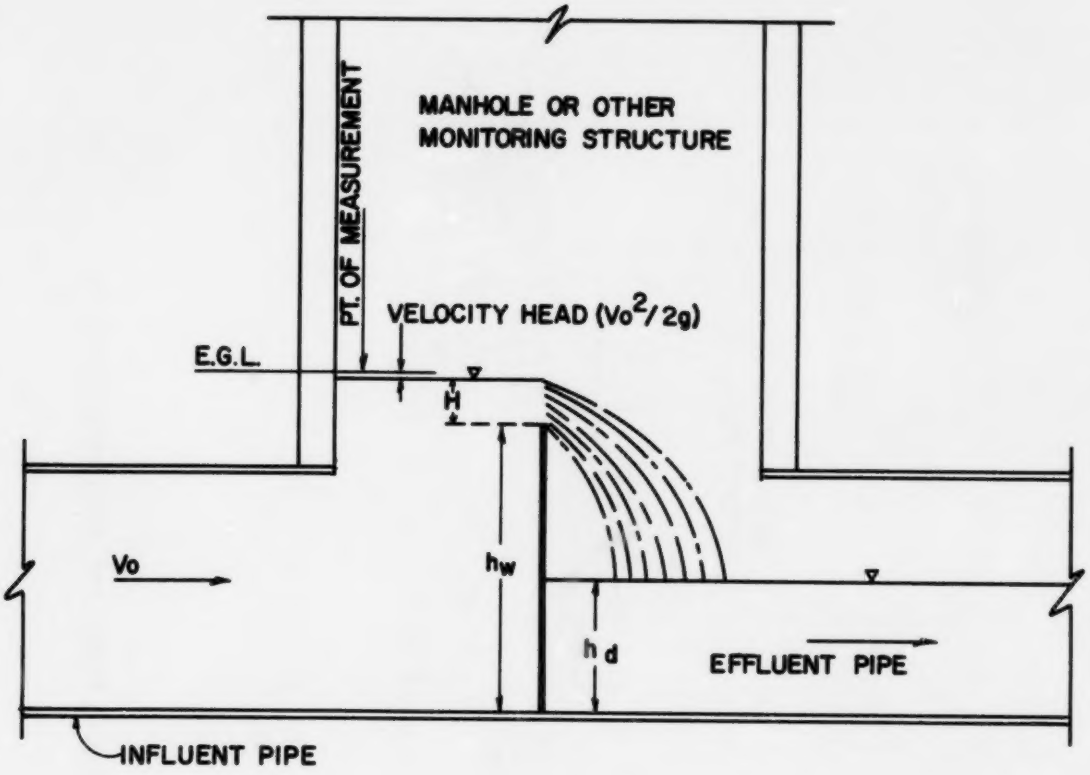
Onondaga County

In the specific case of Onondaga County, there exists a total of 87 active overflow sites. Of these 87 sites, O'Brien & Gere Engineers, Inc. initially monitored 25 sites for both quantity and quality. These 25 sites represented 79 percent of the total combined sewered area of the system. An additional 10 sites were ultimately added to further define the system characteristics. Since the 35 sites monitored comprised such a large portion (85 percent) of the total defined runoff area and represented the entire range of land uses within the combined system, these sites were considered representative of the overall system with characteristics applicable to the unmonitored sites.

EQUIPMENT INSTALLATION

In order to determine the cause-and-effect relationships involving pollutants being discharged from the given combined sewer overflow area, a measure of quantity and quality of the overflow event and a measure of the rainfall producing that overflow is required first (Figure 2). Quantity measurements can be made either on total runoff or total overflow from a given drainage area or both (Figure 3); however, to measure both becomes expensive and generally unnecessary. While both of these measures are useful, the collection of sufficient data to perform a flow balance about the diversion structure is generally sufficient. The collection of data is discussed in greater detail in the flow monitoring section.

In addition to quantity measurements, collection of water quality samples with time is required in order to adequately define the pollutant


MANHOLE OR OTHER MONITORING STRUCTURE
PT. OF MEASUREMENT
VELOCITY HEAD ($Vo^2/2g$)
E.G.L.
H
h_w
Vo
h_d
EFFLUENT PIPE
INFLUENT PIPE

h_w – WEIR HEIGHT

H – DEPTH OF FLOW OVER WEIR

Vo – VELOCITY OF APPROACH

h_d – DEPTH OF FLOW DOWNSTREAM OF WEIR

E.G.L. – ENERGY GRADE LINE

Figure 1. Typical control section and flow monitoring structure.

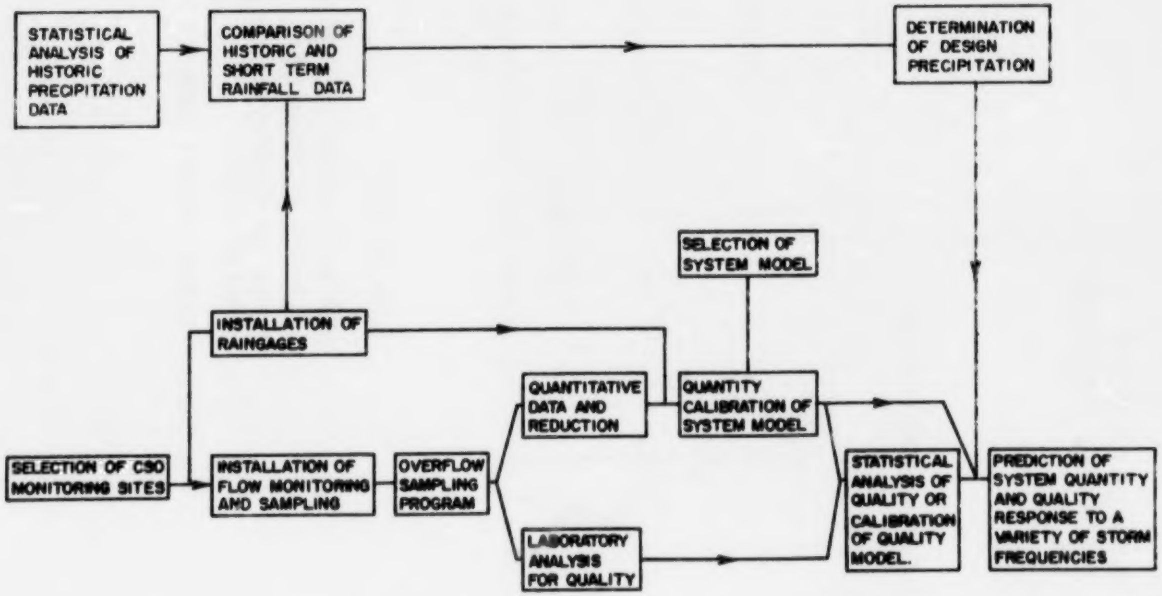

STATISTICAL ANALYSIS OF HISTORIC PRECIPITATION DATA
COMPARISON OF HISTORIC AND SHORT TERM RAINFALL DATA
DETERMINATION OF DESIGN PRECIPITATION
SELECTION OF SYSTEM MODEL
INSTALLATION OF RAINGAGES
QUANTITATIVE DATA AND REDUCTION
QUANTITY CALIBRATION OF SYSTEM MODEL
SELECTION OF CSO MONITORING SITES
INSTALLATION OF FLOW MONITORING AND SAMPLING
OVERFLOW SAMPLING PROGRAM
STATISTICAL ANALYSIS OF QUALITY OR CALIBRATION OF QUALITY MODEL.
PREDICTION OF SYSTEM QUANTITY AND QUALITY RESPONSE TO A VARIETY OF STORM FREQUENCIES
LABORATORY ANALYSIS FOR QUALITY

Figure 2. CSO modeling tasks and data requirements.

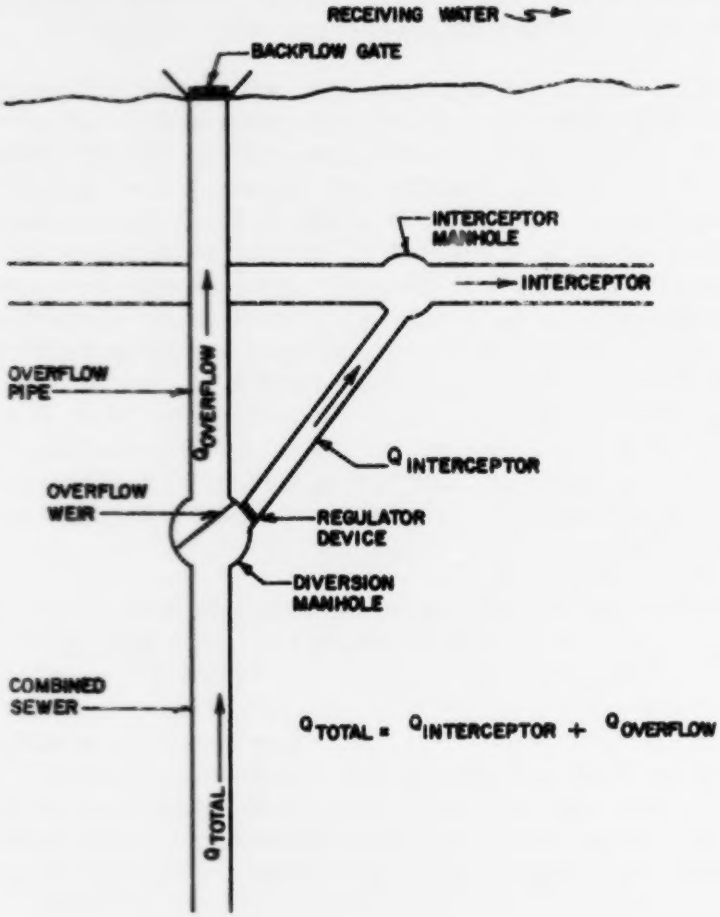

RECEIVING WATER
BACKFLOW GATE
INTERCEPTOR MANHOLE
INTERCEPTOR
OVERFLOW PIPE
Q OVERFLOW
Q INTERCEPTOR
OVERFLOW WEIR
REGULATOR DEVICE
DIVERSION MANHOLE
COMBINED SEWER
Q TOTAL = Q INTERCEPTOR + Q OVERFLOW
Q TOTAL

Figure 3. Typical layout of combined sewer system at the point of overflow.

load (pollutograph) for a given drainage area and given storm. A pollutograph is defined as a plot of the mass rate of pollutant discharge (i.e., pounds per day of suspended solids) versus time (Figure 4).

In order to assess the relationship between rainfall and runoff, the quantity of rainfall falling in a given area must also be determined for each storm. Due to variations in rainfall patterns throughout a community, rain gage placement and density (number per square miles) are critical to a successful monitoring program. In order to limit the standard deviation of the measured coefficient of runoff ("C" factor) to between 10 and 25 percent of mean, it has been estimated that rain gage density on the order of 1 to 5 gages per square mile is desirable (4). Rooftops or open spaces proximate to treatment plants, fire and police stations, and other patrolled facilities are desirable locations for gages since vandalism can be minimized and access is possible 24 hours per day. Care must be taken to install rain gages in areas where they are not sheltered by surrounding trees or structures. For ease of operation and to minimize maintenance, a location with on-site power is desirable but power should be available at all of the above-mentioned facilities.

It is not the function of this methodology to discuss the flow metering and sampling equipment currently available. This subject is addressed in greater detail in two EPA publications which provide an assessment of CSO sampling and measuring devices (3, 5). While many manufacturers produce both flow meters and samplers, few provide a system which integrates the two devices specifically for overflow monitoring. Since portable flow meters are not equipped with time clocks to indicate when samples were collected, an extremely helpful feature of the integrated systems available is that they record this information on the flow meter chart.

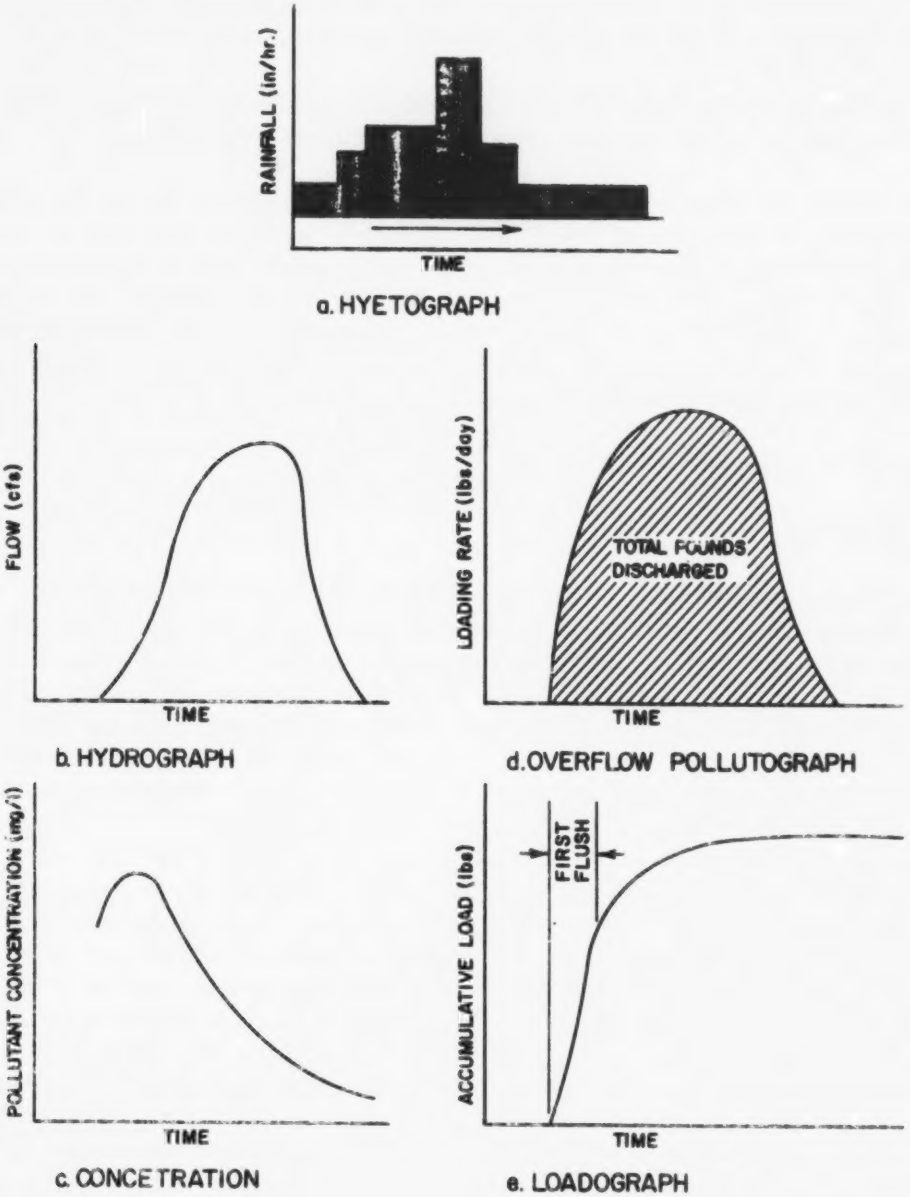
The actual type of equipment applicable to a particular study will depend on the individual monitoring sites selected. The site specific factors requiring evaluation prior to equipment procurement are:

1. Location of flow measurement (i.e., total flow in channel, overflow over weir, or pump station wet well). For these different locations, the range of liquid level and the ease of mounting a level sensor will vary considerably.

2. Space available for equipment installation, which will determine size of equipment to be used.

3. Accessibility to continuous power source.

4. Anticipated frequency of checking operation of monitoring sites, which will determine type of recording chart desirable.



a. HYETOGRAPH

b. HYDROGRAPH

d. OVERFLOW POLLUTOGRAPH

c. CONCETRATION

e. LOADOGRAPH

Figure 4. Plots typical of CSO data presentation.

5. Atmosphere in which equipment will be installed, that will determine type of equipment housing required.

Once these factors are determined and evaluated, the above-mentioned references may be consulted for types of equipment available.

An important aspect of the flow monitoring program is the installation and calibration of the control sections. Whether an open channel or weir is used, the flow versus gage height must be calibrated over a wide range to span the fluctuations in flow encountered during storm events. All control sections should be located in areas where turbulence can be minimized. The accuracy of measurements in turbulent zones is extremely questionable and should be avoided whenever possible.

OVERFLOW SAMPLING PROGRAM

Flow Monitoring

The overall combined sewer study involves the development of relationships between rainfall and sewer system response and between pollutional load and receiving water response. Each of these relationships requires that a different portion of the total flow stream be known. The sewer system model is best calibrated versus total flow from the drainage area, whereas the receiving water model and National Pollutant Discharge Elimination System (NPDES) Permits require that the overflow be known. Depending on the particular drainage basin, it may be more advantageous to measure one or the other of these flows; therefore, the most logical approach involves obtaining enough information through monitoring to perform a flow balance about the overflow structure. To have an accurate measure of each of these components requires making a measure of either total flow or overflow, while at the same time obtaining a record of surcharge condition in the interceptor. This enables an estimate to be made of the flow to the interceptor using hydraulic calculations (see Figure 3). If total flow is to be measured, flow monitoring equipment should be set up in a manhole upstream of the diversion structure, whereas if $Q_{overflow}$ is to be monitored, equipment can be installed in the diversion structure itself. This latter setup is generally more convenient as far as access since these manholes are generally located near the receiving water and away from streets and busy areas. Monitoring flow in the diversion manhole also enables the flow metering device and sampler to be installed in the same structure, allowing the sampler to be triggered by the flow meter. This provides for a greater confidence in the time coordination of the two instruments. Since a pollutograph is the product of flow and concentration at a given point in time, this is extremely critical to determination of both total and instantaneous pollutant loads.

Onondaga County--

In the case of the Onondaga County study, $Q_{overflow}$ was measured and equated to the total wet weather component of flow (6). Measuring $Q_{overflow}$ was considered sufficient since the interceptor had nearly zero ability to handle wet-weather flows. Since most combined sewer systems have wet-weather capacity in the interceptor, equating $Q_{overflow}$ to Q_{total} is generally not accurate. It should be noted that to obtain a true picture of total flow, there is a need for an indicator of interceptor surcharging. While it is possible to establish maximum surcharge height using chalk lines on manhole walls or test tubes mounted at various elevations, the most desirable measure is made with a continuous recorder. Surcharge information enables the instantaneous flow to be computed for the entire storm event and provides all information required for performing a mass balance at the diversion manhole.

The total duration of the overflow sampling program, including both quantity and quality measurements, is dependent on the type of weather encountered. The success of the program is dependent on observing sufficient storms to characterize the system response with an acceptable level of confidence. Based on statistical analysis (7), it appears that between seven and ten storms should be monitored to achieve such confidence; seven to ten storms represent points beyond the "knee" of the curve shown in Figure 5. For example, if ten storms are monitored, the observer can be 90 percent confident that the average runoff coefficient measure for the ten storms will fall within 40 percent plus or minus of its "true" value; if a 68 percent confidence level is acceptable, the estimated percentage error in the observed mean runoff coefficient is reduced to 25 percent for the same number of storms. As may be seen from Figure 5, the percent error can be minimized by increasing the number of storms monitored.

Since the monitoring program relies on the occurrence of at least seven overflow-producing events, the program is at the mercy of nature. In the northeast where a majority of the combined sewers in the United States exist, it is impractical to expect to obtain meaningful data between the months of December and April. During these months, snowfall and snowmelt mask the precipitation patterns and the total runoff precipitation relationship. Also, during periods of snowfall and extreme cold, operation and maintenance of equipment become extremely difficult and sometimes dangerous.

Quality Sampling

Parameters--

The parameters selected to assess the quality of combined sewer overflows are dependent upon the intended best usage of the receiving water. This best usage has been largely defined on a state level. However,

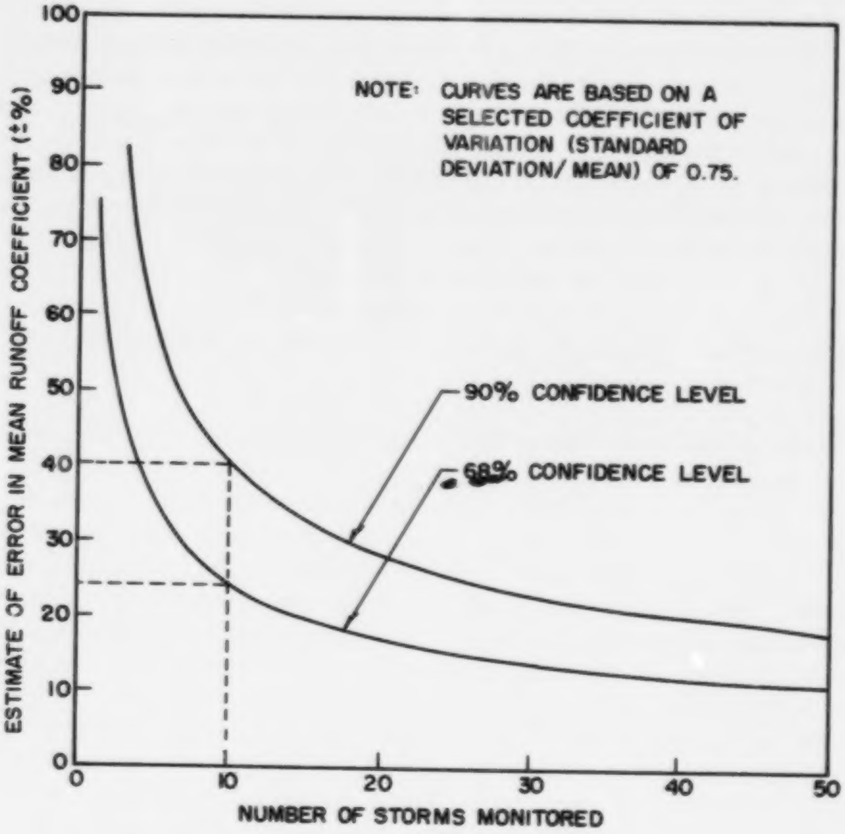


Figure 5. Relationship between accuracy of measured runoff coefficient and number of storms monitored.

practically and realistically, receiving waters should reflect the local interests, particularly in the cases where the receiving water is primarily used by local residents. Section 208 of PL 92-500 provides the means whereby local interests and concerns are channeled through state-designated planning entities for the purposes of establishing classes of use. Consequently, many states are now considering modified classifications for those receiving waters exposed to combined sewer overflows in order to accommodate the water quality variations brought about by overflows. A list of basic parameters for both the system and the receiving waters appears later in this section.

Location--

In the investigation of any overflow system, it is generally recognized that limiting the system monitoring to a certain number of "representative" overflows should be adequate to provide the basis upon which projections for the entire system can be made. The extent to which this approach can be taken is dependent upon the typical or atypical nature of drainage areas and their associated sewer networks. Representativeness of monitoring sites is dependent on: (a) relative land uses in the form of residential, commercial or industrial areas; and (b) the sewer network, including locations of catch basins and the structural condition of the diversion chamber prior to overflow. Other practical considerations include accessibility, physical features, and the size of the monitoring site in question.

Duration--

Duration of sampling should be adequate to capture the peak concentrations of pollutants which normally occur in the initial runoff period. The pollution peak is oftentimes in the vicinity of the "time of concentration" of the associated runoff volume. The total duration of the sampling should also be adequate to capture the decline of pollutant concentrations as well as runoff quantities. Consequently, first estimates could be based on the "time of concentration" associated with a particular drainage area. Real data will ultimately serve as the basis for any needed adjustments to the sampling duration. While the duration must be long enough to capture the "first flush" periods, intervals of sampling must be small enough to adequately define rate changes of pollutant concentrations as well as runoff volume. Figure 4 illustrates typical plots depicting characteristics of an overflow discharge.

Frequency--

The frequency of sampling is important in order to adequately capture the significant changes that occur in both pollutant concentration and runoff volume. Generally it has been found that in as little as five minutes following the onset of runoff volume, significant concentrations can occur. Thereafter, 15-minute intervals have proven to be adequate to define the "first flush" period and the gradual decline of pollution in a discharge. These time intervals have been largely adopted by EPA for the purposes of providing the required NPDES information. A more thorough definition of the variation of pollutant concentrations with time can be obtained by decreasing the size of sample intervals. However, the sampling frequency required to define the quality response of an area is a function of the time of concentration and should be selected on an individual basis.

Samples can be classified as either discrete or composite (8). While composite samples are useful in characterizing pollutant loads which approximate steady state (e.g., wastewater treatment plant influent), they are of little value in depicting the dynamic nature of storm-related sources. In order to adequately define the variations described above, discrete sampling is necessary at some prescribed time intervals. The results of such sampling, when combined with the continuous recording of flow, provide the necessary data for the construction of discharge pollutographs and loadographs, as shown in Figure 4.

Automation--

Since the measurement of representative overflows for a given sewerage system will normally require a significant percentage of the total overflows, and rainfall events can occur during the more inconvenient hours of the day, automatic sampling has been commonly recognized as being more cost-effective than manual sampling. Equipment is available which allows such sampling to be coordinated with continuous recordings of sewer flows. Many NPDES permits require the measurement of 25 percent of Type 1 discharges, which are those that are known to overflow in excess of 20 times a year for as many as four separate and independent rainfall events. Thus, for the purposes of meeting such requirements and at the same time to obtain the needed data for overflow investigations, the need for automation in large systems becomes obvious.

Manual Sampling--

It is, however, possible in smaller systems where manpower is available that the necessary data could be collected manually. Manual sampling can be done so as to represent a waste stream and in addition can be done at such time intervals as to more accurately coincide with flow variations. In addition, malfunction of sampling devices can be eliminated. The primary drawback of manual sampling is that manpower must be deployed at the first hint of rain or risk missing the all important "first flush" period. On the basis of this alone, manual sampling for the sewer system is generally discouraged.

SECTION 5

RECEIVING WATER SAMPLING

GENERAL

The governing criterion for the abatement of any pollution is the impact on water quality. Despite the lack of data in the past, it has been generally recognized that future programs will require a heavy emphasis on impact data. In its March 1976 report, the National Commission on Water Quality (9) stated:

> "We also find that there is still a major lack of adequate information. We simply do not know enough. There are not sufficient data to tell us exactly how bad the water was, or how much better it is getting. The measuring and analytical techniques and predictive methodologies are not good enough in many instances to tell us the scope and value of incremental water quality improvements. If billions of dollars are to be invested wisely, we must have more and better data collected over an adequate term of years."

This condition still prevails today. Programs must be initiated now and conducted for some years to come in order to have the long-term data base necessary for rational decisions. A "Report to Congress" by the Comptroller General's Office issued December 1976 (10) concurred with the Commission's concern and recommended that EPA:

> "Determine whether existing resources at the State level are adequate to implement effective comprehensive water quality planning and data collection programs. If existing resources are inadequate, additional resources should be requested from the Congress."

In the case of combined sewer overflows, the need for receiving water data is particularly important since there is the risk that large amounts of dollars may be needed to remove relatively small amounts of pollutants.

Also, the water quality impact may be of such a transient nature that the benefits derived may not be cost effective.

WATER QUALITY CONCERNS

Parameters for overflow discharges should reflect the water quality criteria and hence should be the same as those measured for the receiving water. The exceptions are those biological parameters that reflect the aquatic food chain in a receiving water. For the purposes of this methodology, the primary concerns of stormwater impact on a lake are: (a) pathogens; (b) dissolved oxygen; (c) nutrients; and (d) acute toxicity.

Several bacterial groups, including the total coliform (TC), fecal coliform (FC) and fecal streptococcus (FS) groups have been used to indicate the probable presence of pathogens. Indicator groups are used since their presence is more easily and rapidly detected, and their correlation to the presence of pathogens is widely documented (11, 12). The fecal coliform group is generally recognized as the single most reliable indicator. The fecal streptotoccus group is useful in that a ratio between this group and those of the fecal coliform group can indicate the source of the fecal contamination. The ratios of fecal coliforms to fecal streptococci have been interpreted as follows (13):

FC/FS	Source of Pollution
>4	Human
0.7 - 4.0	Human and Animal
<0.7	Animal

The dissolved oxygen (DO) concentration of a lake is influenced by a variety of physical, chemical and biological processes. The velocity and depth of the water and its altitude and temperature are all physical constraints on the amount of DO in a body of water. Oxygen is consumed during chemical or biochemical reactions in the water column or in the sediments. In the absence of oxygen, anaerobic processes predominate, leading to odors and other septic conditions. Oxidizable waste products discharged into municipal and industrial wastewaters may reduce DO to very low concentrations, even to zero. Because aquatic organisms consume oxygen during respiration and because aquatic plants, particularly algae, produce oxygen during photosynthesis, DO concentrations may vary significantly during the course of a day. DO standards are often established to insure the sustenance and well being of a certain desired fish population. For example, in many states, DO standards are based on the sustenance and well being of trout.

Nutrients, in addition to DO, play the major role in determining the trophic status of the lake. Eutrophication of a lake occurs when there is an excess of nutrients, causing an enriched water system. Eutrophication of a lake can have direct as well as indirect effects on public health. Toxics from certain algae species and parasitic organisms have been suspected as the cause of certain ear, nose and throat infections. Intense algae blooms can be a nuisance to recreational uses such as swimming and boating. Nitrogen and phosphorus have been identified as major elements which, in excess concentrations, can cause eutrophication. Phosphorus is an essential plant nutrient that is often critical to plant productivity because of its marginal concentrations in many receiving waters. Addition of this material associated with cultural activities often results in stimulation of plant productivity. The artificially-induced increased productivity is referred to as "cultural eutrophication". Major sources of phosphorus in waterways include industrial wastewater discharges, municipal wastewater discharges, and agricultural and urban stormwater runoff.

Toxics are a major concern in that they can have the most immediate, severe and direct effect on either the aquatic system or public health. Unfortunately, toxics are by their nature specific and not detectable by conventional laboratory equipment. Thus, either prior knowledge of a toxic material must exist or a periodic monitoring program must provide for a scan of suspect materials. In consideration of the new, extensive and always increasing list of toxics, as defined by EPA under provisions of the Toxic Substances Control Act, projects can rarely accommodate analyses for toxics; the only exceptions are those heavy metals that have been commonly associated with runoff and can be analyzed relatively easily. Since a material is toxic by virtue of the adverse effect it has on the water system in question, a reasonable alternative would be to utilize the BOD test as an indicator of the existence of any such material. If a decreasing trend in BOD is consistently noted with a decreasing dilution ratio (ml dilution water used/ml sample used), the sample probably contains an inhibitory or acute toxic substance. It would then warrant further investigation into the source and nature of the material.

Table 1 lists the parameters to be considered for analysis in both the CSO system and the receiving water. Certain of these parameters require field measurement, as indicated by the table. Some analyses can be considered optional in that they can be measured in place of other parameters. Chemical oxygen demand and total organic carbon have both been considered as substitutes for the BOD test. However, in terms of impact on the aquatic system, the BOD test still represents a more direct measure of actual demand as it occurs in the receiving water and, as described above, can indicate inhibition or toxicity. Certain biological parameters are direct measures of the food chain within the receiving water. The extent to which measurements are required depends largely on the necessity of having to measure the balance of the food chain. In most overflow impact studies, such detail would not be warranted unless toxins produced by one or more of these organisms are so in evidence that control procedures would be required.

TABLE 1. WATER QUALITY PARAMETERS

	Discharges & Tributaries	Lake
Field Measurements	Flow	Lake currents
	Dissolved oxygen	Dissolved oxygen
	Temperature	Temperature
	pH	pH
		Transparency
Biological Parameters		Plankton
		Periphyton
		Macrophyton
		Macroinvertebrates
		Fish bioassays
	ALL LOCATIONS	
Laboratory Analyses	Fecal coliform	Total phosphorus
	Fecal streptococcus	Ortho-phosphorus
	BOD_5	Poly-phosphorus
	BOD_{28}	Chlorides
	Chemical oxygen demand*	Sulfates
	Total organic carbon*	Sulfides
	Total solids	Alkalinity
	Dissolved	Hardness
	Suspended	Heavy metals
	Volatile and fixed	Lead
	Settleable	Copper
	Nitrogen compounds	Zinc
	Organic	Chromium
	Nitrite	Mercury
	Nitrate	

*Optional

SAMPLING LOCATIONS

The objective of receiving water sampling is to define pollutant concentrations at all significant discharges and tributaries to the lake and in the various zones within the lake prior to, during and following storms. All major inputs should be identified in order to establish a reasonable materials balance throughout the storm. Any tributaries to the lake should be sampled so as to bracket the segments that receive combined sewer overflows. In this manner, upstream non-point pollutant contributions can be identified and compared to those coming from the sewer system. In some cases it may also be desirable to isolate those areas served by a separate sewer system, as opposed to a combined system, in order to determine the significance of urban stormwater. Minor tributaries need not be monitored if they are known to contain a relatively insignificant quantity of pollutants. Using Onondaga Lake as an example, Figure 6 illustrates the major pollutant sources that should be identified in any sampling program.

In stratified lakes there exist two major zones which should be sampled in most limnological investigations. These zones are the epilimnion (upper water) and hypolimnion (lower water). They are separated by a zone of rapidly changing density (metalimnion), resulting in two relatively distinct and independent volumes of water. In shallow lakes, where such a separation does not exist, measurement at one depth may be adequate. Preliminary investigations can be conducted to determine the variation of temperature and dissolved oxygen to determine if stratification exists and if multi-depth sampling is required. Depth profiles should be taken throughout the study to chart movement of the metalimnion so that sampling depths can be adjusted.

Transverse movement in a stream is often ignored in simple one-dimensional modeling. In the case of a lake, the transverse direction is not distinguishable from the longitudinal direction. Generally, stream sampling emphasizes time of travel in the longitudinal or downstream direction for the purpose of tracking both the dissolved oxygen sag and the recovery zone of the stream. Within a lake, "downstream" can be in any compass direction, depending upon such external influences as tributary currents, wind, and the consequent internal oscillations referred to as the seiche effect; the lunar influence is not significant in the smaller lakes.

The essential difference between a stream and a lake emphasizes the need for a greater knowledge of lake currents as they affect circulation patterns of a lake. Based on these patterns, zones within a lake can then be separated, sampled and identified. Segmentation of a lake into zones is particularly useful in order to distinguish certain tributaries and shoreline areas of the lake, where contact recreation will take place, from the deeper areas of the lake. The latter areas are more apt to represent the major

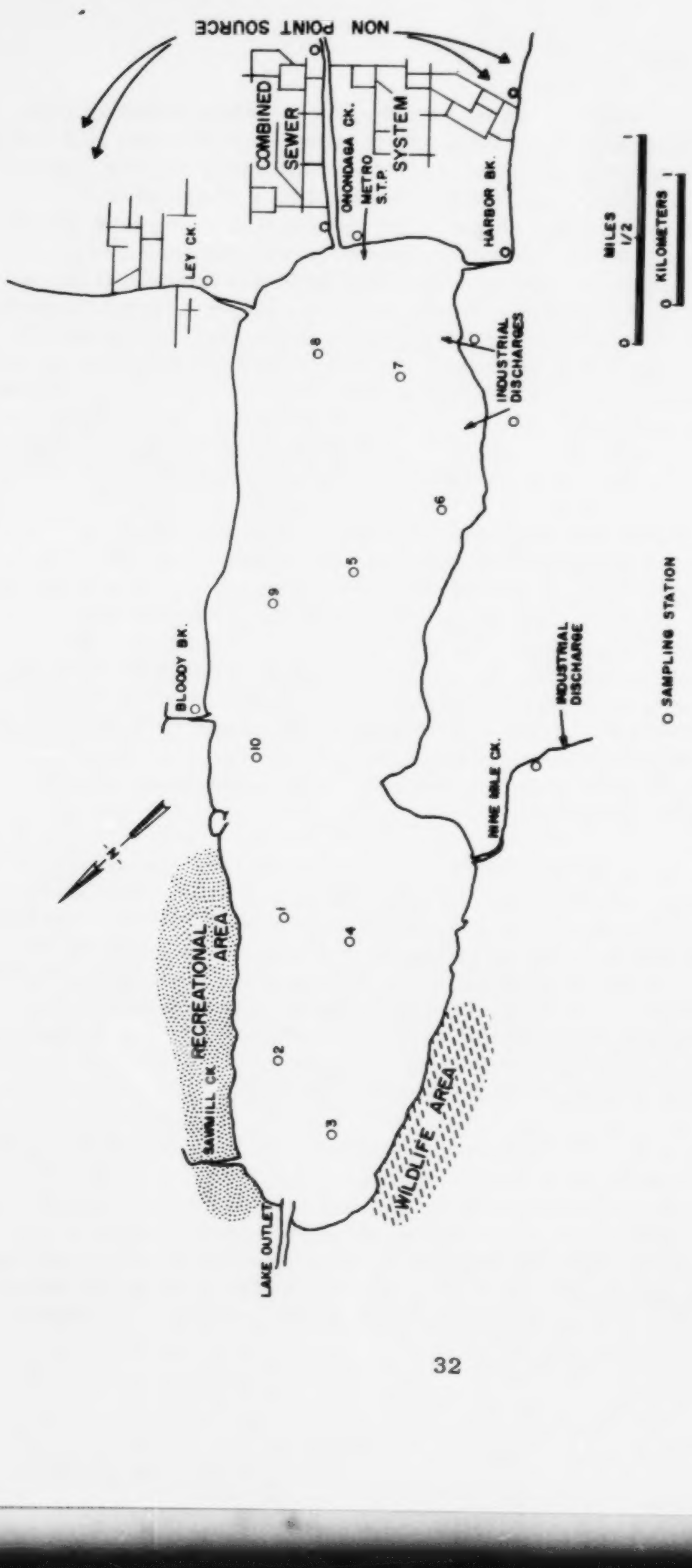

NON POINT SOURCE
COMBINED SEWER SYSTEM
ONONDAGA CK.
METRO S.T.P.
HARBOR BK.
LEY CK.
INDUSTRIAL DISCHARGES
MILES
0
1/2
0
KILOMETERS
O SAMPLING STATION
INDUSTRIAL DISCHARGE
NINE MILE CK.
BLOODY BK.
N
RECREATIONAL AREA
SAWMILL CK
WILDLIFE AREA
LAKE OUTLET
1
2
3
4
5
6
7
8
9
10

Figure 6. General plan and sampling locations for Onondaga Lake.

lake water quality, whereas areas directly exposed to shoreline activity will reflect more temporal effects. Figure 7 illustrates an example of lake segmentation. The relationships considered within each segment are presented in Section 8 of this report.

DURATION OF SAMPLING

The duration and frequency of sampling must be adequate to profile pollutant loads in much the same manner as outlined for overflow discharges.

The number of storms for which the receiving water should be sampled is dependent upon the adequacy with which the resulting information can relate water quality of the lake to storm pollutants. One approach accomplishing this objective is to conduct the sampling until the impact of the "design" storm is actually measured. The "design" storm has come to mean that storm for which abatement facilities are planned. While this approach would yield the most directly usable impact data, sampling of the design storm is aimed at an elusive target and can result in extensive expenditures for field work.

Another approach to accomplishing the objective is to conduct only enough sampling to define the essential functions within the lake and use mathematical projections to calculate the impact of a variety of storms. In the absence of suitable and practical guidelines for the selection of the design storm, the use of mathematical projections has become necessary in order to evaluate the wide variety of conditions often imposed on the receiving water. It is likely, moreover, that sufficient field data will have been collected to develop essential relationships within the lake before any preselected design storm is encountered. In addition, mathematical modeling techniques provide a great amount of flexibility to evaluate the combined sewer system response to a variety of rainfall patterns and sewer system modifications. Modeling techniques available for this purpose are covered in Section 7 of this report.

FREQUENCY OF SAMPLING

Frequency of sampling of the tributaries and lake must be adequate to establish the altered character of the ecosystem associated with a storm occurrence. It is important, therefore, to measure stream and lake conditions before, during and after each storm. The following sampling schedule was adopted initially to document the impact of storms monitored on Onondaga Lake during the period of June through September 1976:

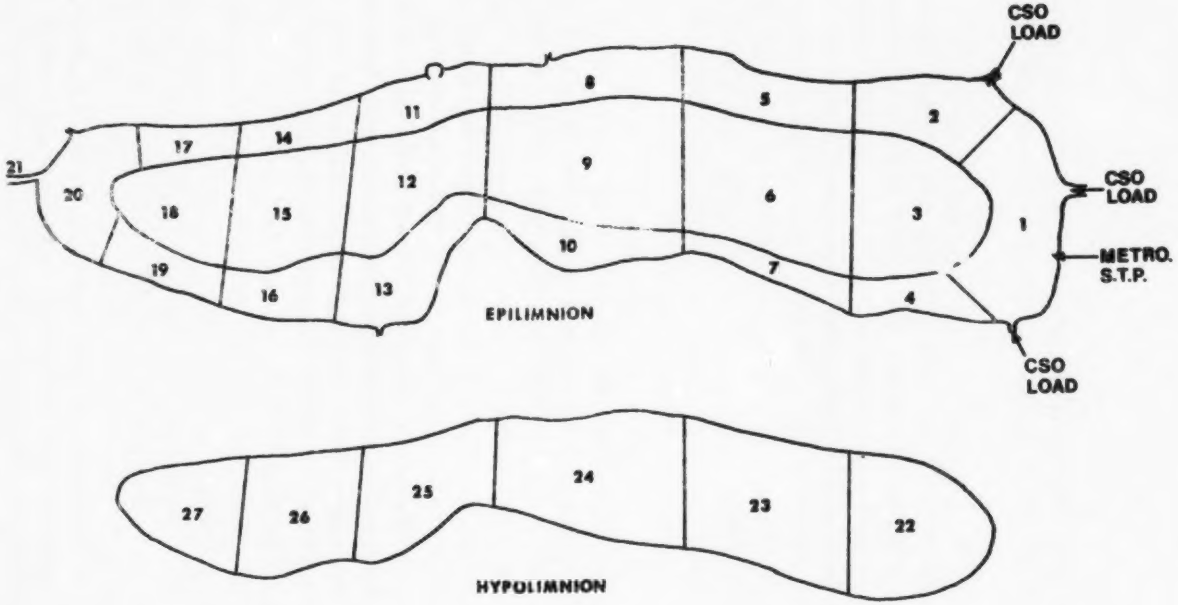

CSO LOAD
CSO LOAD
METRO. S.T.P.
CSO LOAD
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
EPILIMNION
22
23
24
25
26
27
HYPOLIMNION

Figure 7. Model segmentation.

Sample Period	Frequency of Sampling Lake Stations	Tributary Stations
12 hours prior to storm runoff	1	1
During 12-hour storm	3	6
3-day period following storm	6	9

As the sampling phase of the study progressed, some alterations to the frequency were made, reflecting specific storm durations, weather, nightfall and evaluated data. The pre-storm sample was particularly difficult to obtain since long-range weather forecasting is often inaccurate. Prolonged storms required modification of the sampling schedules to obtain sufficient post-storm measurements.

AUTOMATION

Unlike the overflow discharges, receiving water locations, particularly in a lake, do not lend themselves easily to automatic sampling. Navigational restrictions and equipment costs generally rule out the installation of automatic equipment in a lake. Depending on the size of a tributary, these restrictions may also apply to stream measurements.

A major concern in any sampling is the representativeness of the sample. A lake or stream is more likely to show variations of flow and pollutant concentration through the cross section of flow than is a piped discharge. Thus, multiple sampling ports may be required if automatic sampling is to be considered. Although, in theory, multiple sampling points may appear reasonable, such installations are generally subject to loss and destruction from the exposure to the elements common to receiving water locations; such installations are generally to be discouraged. If "cross sectional" variation can be considered negligible, then automatic sampling may be feasible for discharges and tributaries. Automation notwithstanding mechanical failures, would assure the capture of "first flush" periods in the stream regardless of the time of day or night. However, there often is a lag period between the start of a storm and the time when the impact of the storm is noticeable in a lake, manual sampling of the lake can commence the following morning, if the storm occurs at night.

SECTION 6

DATA BANK

An important aspect of any study is the convenient storage of all data in a form that is easily reviewed and analyzed. For studies involving water quality sampling with a large volume of analyses, it is of utmost importance to be able to store, process and retrieve the data as rapidly as possible. As shown on the flow chart (Figure 8), the ideal method of reviewing data proceeds from sampling and analysis to computer input and output, to laboratory for review, and back to the computer for corrections.

Once the data has been checked by laboratory personnel for accuracy it should then be reviewed by the engineering or planning staff for overall applicability. Since large sums of money are being spent on data collection and laboratory analysis related to CSO studies, it is extremely important, as the project progresses, to review the data prior to establishing the parameters to be analyzed during subsequent storms. Data review ensures that dilutions for certain laboratory analyses have been properly selected, and if not, provides time to correct these inaccuracies before the next sampling event. The comparison of trends in both the receiving water and the system discharges will focus the reviewer's attention on areas of critical concern and maximum impact. This detailed review of data collected will highlight monitoring locations where more or less intensive studies are dictated, where monitoring stations should be added, and, possibly, where sampling can be eliminated. It also will reveal parameters that fail to reflect storm impact and enable these analyses to be eliminated. While ideally these data should be stored and retrieved from the computer and reviewed prior to embarking on the next sampling event, this procedure is not always practical.

The file structure should include sufficient identifiers so that data collected can be recalled from the data bank by location, storm, date and time, and parameter name. For location it is desirable to have two identifiers available, one for location in plan and the other for the depth from which the sample was collected. The data base should be established so that any of the primary identifiers, such as all BOD_5 data associated with Location #7 on a given date, or all dissolved oxygen measurements

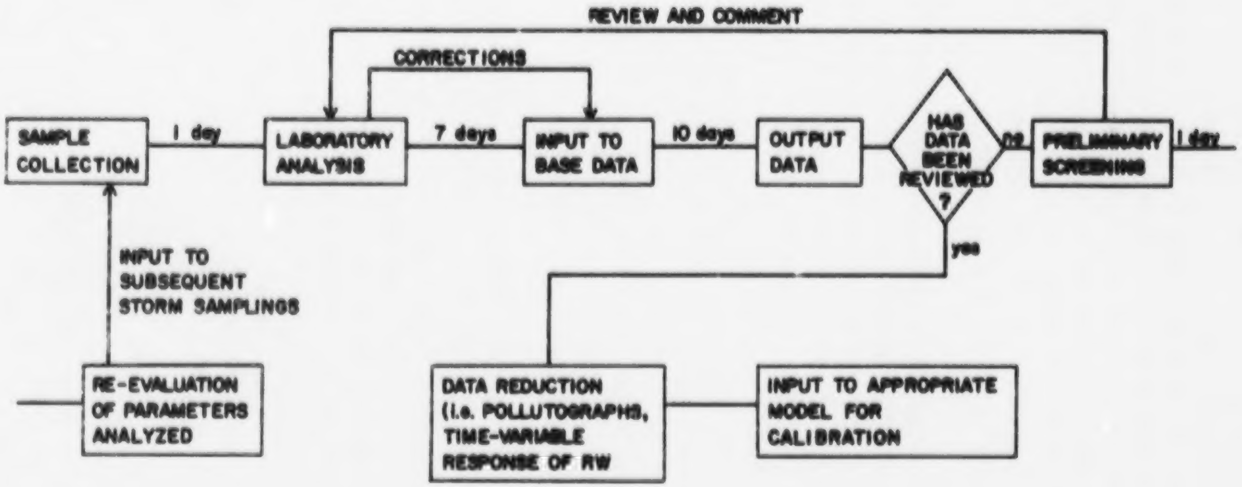

REVIEW AND COMMENT
CORRECTIONS
SAMPLE COLLECTION
1 day
LABORATORY ANALYSIS
7 days
INPUT TO BASE DATA
10 days
OUTPUT DATA
HAS DATA BEEN REVIEWED ?
no
PRELIMINARY SCREENING
1 day
yes
INPUT TO SUBSEQUENT STORM SAMPLINGS
RE-EVALUATION OF PARAMETERS ANALYZED
DATA REDUCTION (i.e. POLLUTOGRAPHS, TIME-VARIABLE RESPONSE OF RW
INPUT TO APPROPRIATE MODEL FOR CALIBRATION

Figure 8. Summary of data review process.

associated with a given location. Identifiers enable all significant operations to be readily performed on the data.

The most useful method of presenting tributary data is in the form of a pollutograph or pollutant load (pounds per day) versus time plot for a given location (Figure 4). For lake stations, a time-varying plot of concentration for each station is the most convenient and usable method of presentation. Another useful measure for comparing tributary contributions is the area under the pollutograph (Figure 4), or the total pounds of pollutant discharged per storm. A further refinement of this calculation would involve total contribution per day or even total contribution per hour; however, rarely is sampling accomplished frequently enough to justify this detail.

In addition to providing for easy perusal of data, an organized data base makes statistical analyses much easier to perform, particularly in the critical case of data collected from the combined sewer system. Statistical analyses performed to obtain both the relationship of the quantity of runoff to rainfall and the quality of overflow to time or runoff are useful in determining the quantity and quality of predicted overflows.

ONONDAGA LAKE

The Onondaga Lake data base was set up as described in the preceding paragraphs. This level of identification permitted the retrieval of data in all the output forms found necessary throughout the project.

For Onondaga Lake, portions of the data were available for review in handwritten form, while at no time were data from the computer available prior to the next sampling event. In retrospect, this could have been a major time- and money-saving tool. Perusal of the entire data base "after the fact" shows that many of the parameters could have been eliminated or the frequency of analysis reduced at several of the sites. Examples of sites that could have been totally ignored were Bloody Brook and one of the industrial discharges (Figure 6); parameters that could have been measured on a reduced frequency included all metals, chlorides at all but NineMile Creek, and elimination of all analyses at the East Flume with the exception of total Kjeldahl nitrogen.

SECTION 7

MATHEMATICAL MODELING OF COMBINED SEWER SYSTEM

OBJECTIVE OF MODELING

The objective of modeling the sewer system in CSO and stormwater analyses is to develop a mathematical representation of the hydrologic, hydraulic and water quality aspects of the drainage area and wastewater collection network. The model, once calibrated, can be used for predicting both the quantity and quality of CSO at specified design storm conditions. Modeling also reduces the amount of data gathering required. Once an adequate number of quantity and quality measurements are made over a range of storm types, the model enables the prediction of results for any reasonable set of storm conditions. It is not feasible in most instances to measure rainfall, CSO or stormwater quantities and quality, and receiving water quality for the period of time necessary to ensure that appropriate design conditions will be captured. Thus, the proper balance between actual field monitoring and mathematical modeling must be determined for each particular study.

All stormwater models, with the exception of simple "desk-top" models, require calibration and verification of the predicted to the measured data, if results are to have credibility. Calibration of the model parameters and coefficients is an integral part of overall modeling procedure in that the finer the model is calibrated, the more confidence can be placed in its predictions. Calibration and verification require sets of measured field data. The measured data should be taken over a range of storm conditions if at all possible. Some data, such as drainage area characteristics, dry-weather flow information, and collection system configuration, do not have to be obtained in the field. These data can often be found in aerial photographs, topographic maps, sewer plans, planning and engineering reports, and other sources. While it is not necessary to field-measure these characteristics, each area should be field-checked to insure the accuracy of these sources, to point out any discrepancies, and to give the modeler a visual perception of the area. Rainfall and runoff quality and quantity, however, must be measured in the field in a time-coordinated manner. Rainfall data can be obtained from the National Oceanic and Atmospheric Administration (NOAA), National Climatic Center, Federal

Building, Asheville, North Carolina. This information is available on computer tapes for all continuously-operating NOAA weather stations.

In general, the overall objectives and budget constraints of the stormwater study will dictate the level of both the field sampling and the mathematical modeling. If the study is to result in the preliminary, or actual, design of CSO or stormwater abatement facilities, the level of effort associated with the modeling and data gathering will be great. On the other hand, if the results of the study are to be used as a preliminary assessment of pollutant loadings and their impact on a particular waterway, then the monitoring and modeling requirements will be relatively small, with most of the effort placed on relatively simple modeling techniques.

TYPES OF MODELS AVAILABLE

Levels of Analysis

There are a number of mathematical models currently available for CSO and stormwater analyses. They range from the "desk-top", hand-calculated models, such as the simple "rational formula", to the sophisticated EPA Storm Water Management Model (SWMM) (15, 16). Three categories have been suggested for all stormwater assessment models, based on their applications, as shown in Table 2 below.

TABLE 2. CATEGORIES OF STORMWATER MODELS

Level	Application
I	Problem Assessment
II	Planning
III	Event Analysis

The mathematical models used in stormwater analyses increase in complexity from Level I to Level III. Also increasing are the data requirements associated with the model calibration and actual operation. Table 3 further describes the three categories of stormwater assessment in terms of model complexity and characteristics.

Some models are capable of being used for more than one application. For example, the EPA SWMM model is considered a single event, or Level III model, but it can also be operated continuously, or as a Level II model. Those models which do not require the use of computers, such as the EPA-Level I SWMM; the URS, Inc. procedure; and the EPA Areawide Assessment Procedures Manual method, are considered Level I, or problem assessment models (7, 17, 20, 21). In addition to the continuously-operated EPA SWMM, other planning, or Level II, models include the U.S. Army Corps

TABLE 3. STORMWATER ANALYSIS LEVEL AND MODEL COMPLEXITY (17)

Analysis Level	Model Type	Model Complexity	Purpose of Model	Model Characteristics
I	Desk-top	Low to medium	Problem assessment, preliminary planning, alternative screening.	No computers. Equations, nomographs based on statistical analyses of many years of records.
II	Continuous simulation	Low to medium	Problem assessment, planning, preliminary sizing of facilities (particularly storage), alternative screening. Assess long-term impacts of designs.	Program of few hundred to few thousand statements. Uses many years of rainfall records with daily time steps, or worst two years with hourly time steps. May include flow routing and continuous receiving water analysis.
III	Single event simulation	Medium to high	Analysis for design, detailed planning.	Program to cover 10,000 statements. Higher modeling precision, from rainfall through sewers, possibly to receiving waters. Short-time steps and simulation times. Fewer alternatives to be evaluated.

of Engineers' STORM and EPA Simplified SWMM (SSWMM) (21, 22).

A number of models of all levels of complexity are capable of predicting only quantity. Others are only applicable for separate stormwater systems since dry-weather flows are not readily considered. Many of the available models are continually being updated and modified to reflect user-supplied suggestions or better knowledge of actual system responses. A number of models are presently being revised to include quality and/or dry-weather flows to be applicable for CSO studies. EPA has recently published four reports which analyze most of the currently-available stormwater models (7, 17, 23, 24). It is recommended that these reports be reviewed by those planning to use a mathematical model for CSO or stormwater analyses since the advantages and disadvantages of the models are presented with respect to various applications. An important consideration should be that the model selected for any study should be the simplest that can adequately perform the necessary analyses.

The two models that were used in the Onondaga County CSO Study, SWMM and SSWMM, are discussed in greater detail below.

EPA SWMM

The EPA SWMM is one of the most comprehensive yet flexible stormwater models currently available. Dry-weather flows can be considered, runoff quality as well as quantity can be simulated, sewer routing is included, and it can be operated in either a single event or continuous mode. SWMM, being relatively complex, requires a large amount of input data and a relatively large computer. First introduced in 1971, the model has been updated on several occasions to reflect both changes in the state-of-the-art of stormwater modeling as well as to correct errors in the program itself.

The model consists of five basic components: the RUNOFF, TRANSPORT, EXTENDED TRANSPORT (EXTRAN), STORAGE-TREATMENT (S/T), and RECEIVING WATER (RECEIV) BLOCKS. Figure 9 shows the relationship of the blocks to the model's central component, or the EXECUTIVE BLOCK.

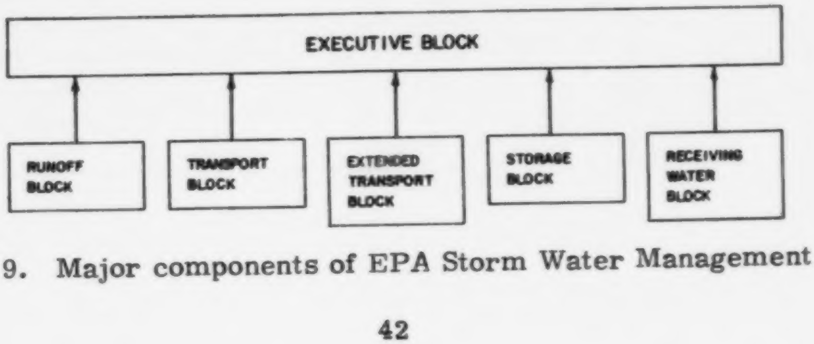


Figure 9. Major components of EPA Storm Water Management Model.

The RUNOFF BLOCK simulates the rainfall and subsequent runoff processes including overland, gutter and/or pipe flow. Drainage basin characteristics such as size, slope, imperviousness, roughness and other factors are taken into account. Land use and pollutant accumulation of street surfaces are also considered when runoff quality is simulated. Also taken into account is the surface storage on the impervious and pervious areas, the soil infiltration capacity, and flow routing through the gutter and/or pipe network. More detailed sewer routing usually takes place in one of the transport blocks, although this is not always warranted. The results of the RUNOFF BLOCK simulation for both quantity and quality can be the input to other blocks of SWMM or can be used by themselves.

The TRANSPORT BLOCK is used to route the input hydrographs from the RUNOFF BLOCK through the assigned sewer network to either treatment or storage facilities, direct discharge, regulated discharge, or to additional transport networks. TRANSPORT does not simulate surcharging, flow reversals nor looping as it can only simulate one-directional flow.

EXTRAN is used instead of TRANSPORT where surcharging or backflow problems are encountered. This block is more costly to run than TRANSPORT due to the relatively small time-step required to account for model instability problems.

Both transport blocks route quality along with the quantity, taking into account dry-weather flow and pollutant scouring in the sewers in addition to the pollutant washoff from RUNOFF.

S/T is used to simulate storage and treatment alternatives. Input hydrographs can come either directly from RUNOFF or from one of the transport blocks. A number of treatment processes are included in the block, each with assigned pollutant removal efficiencies.

RECEIV is used to simulate the hydrologic and water quality impact of actual or predicted discharges on the receiving water. RECEIV can accept input from any of the other blocks or it can be used independently. It is a dynamic water quality model in that it can simulate the effects of time-varying waste loads, such as CSO or stormwater discharges. The block is similar in composition to EXTRAN in that backwater effects, such as encountered with tide cycles, are taken into consideration.

EPA Simplified SWMM (SSWMM)

Due to the complexities of Level III SWMM, its use is not recommended for problem assessment or for the preliminary sizing of storage and treatment facilities. SSWMM was developed to fill the needs of those requiring a model with both problem assessment and planning capabilities, yet requiring a less complex, more economical tool than a Level III model. SSWMM, a Level II model, has greater detail than the Level I desk-top model. Field data is required for model calibration and model operation, but not to the same order of magnitude as for detailed SWMM or other similar models.

SSWMM consists of a number of small independent computer programs for its five major modeling tasks. Figure 10 shows these tasks along with their interrelationships to each other. Only three tasks -- rainfall characterization, storage-treatment balance, and receiving water response -- require the use of a computer.

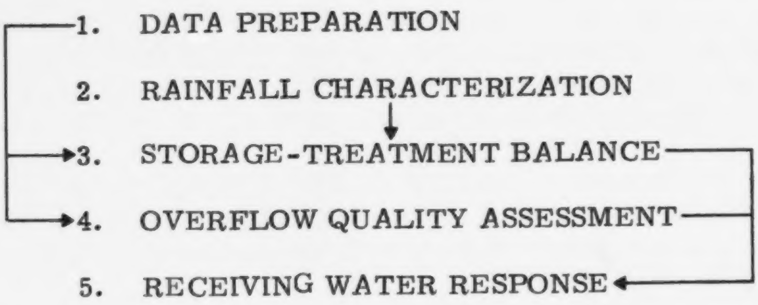

1. DATA PREPARATION
2. RAINFALL CHARACTERIZATION
3. STORAGE-TREATMENT BALANCE
4. OVERFLOW QUALITY ASSESSMENT
5. RECEIVING WATER RESPONSE

Figure 10. Interrelationship of tasks in the Simplified Storm Water Management Model

The model differs in a number of respects from detailed SWMM. Unlike SWMM, which can be operated in a range of time-steps to correspond to the particular rainfall hyetographs, or drainage or transport network characteristics, SSWMM can only be run on a one-hour or daily time-step to correspond to computerized rain tapes. As with most planning models, SSWMM can only be run in a continuous mode. Runoff is calculated in a rather simple fashion using a runoff coefficient "K" (the gross runoff coefficient) similar to that of the "rational formula". However, the runoff calculations are more detailed than the "rational formula" in that runoff volumes are computed for each rainfall. The major tasks involved with the use of SSWMM are discussed in the four paragraphs that follow.

Rainfall Characterization--

Five small computer programs are included in SSWMM to analyze the data on the rain tapes from the National Climatic Center. These include programs which define storm events, sequence storms and rank storms by assigned parameters. Once the data is analyzed the rainfall is subjected to runoff, storage, treatment and/or overflows in the storage-treatment program.

Storage-Treatment Balance--

The storage-treatment program of SSWMM can be operated either hourly or daily. Interceptor capacities, storage rates and treatment rates are set with overflows occurring when the various rates are expected. All of the rates can be modified independently to compare a number of alternatives in handling and treating the runoff.

Overflow Quality Assessment--

Overflow quality is not determined within the actual model, but is calculated manually either using literature pollutant loading functions or statistically manipulating actual, measured quality data. The volume of overflow, as obtained in the storage-treatment program, is paired with the calculated quality data obtained through the above analysis. Dry weather flows and quality not included in the model should be included with these hand calculations.

Receiving Water Response--

The response of the receiving water to the stormwater discharges is simulated through the receiving water program. The use of an existing receiving-water quality model, if any, is recommended in preference to the one provided in the model. The receiving-water quality model included with SSWMM is general in nature and requires calibration prior to use as a predictive tool; it is also a steady-state model and does not simulate dynamic loadings adequately for all applications.

Comparison of Detailed Single-Event SWMM and Simplified SWMM (SSWMM)

Both SWMM and SSWMM have their advantages and disadvantages in range of application, level of complexity, cost of operation, and data requirements. Thus, a direct comparison of the two models is not totally applicable since both models would not necessarily be considered for the same specific situations. Table 4 highlights some of the major features of each.

Complementary Model Usage

As in the case of the Onondaga County CSO studies, it may be desirable to employ both the simplified and detailed models. SSWMM can be used initially to describe some basic rainfall-runoff or rainfall-overflow relationships for the key drainage areas. These relationships can be used preliminarily to locate storage and treatment facilities in addition to assessing water quality impacts in the receiving waters. A further use of such relationships is in determining the design storm or storms. Although the rainfall data for SSWMM is in hourly increments, the results of the model will give a reasonable picture of the sensitivity of a drainage area to rainfall and overflow conditions spanning long periods of record.

TABLE 4. COMPARISON OF SINGLE-EVENT SWMM AND SSWMM

	Single-Event SWMM	SSWMM
Model complexity	High	Low
Storage core requirements	350K	40K
Cost of operation	High	Low
Data requirements	High	Moderate
Rainfall data	Multi-hyetographs can be used along with a range of time-steps in the order of minutes; 1-hour rain data for multi-years can also be used.	Single hyetograph with 1-hour time-step; 10-20 years of data preferred.
Dry weather flow and quality	Included	Not included
Flow routing	Included in either one of three blocks	Not included; only interceptor capacity at overflow point
Surcharging-backflow	Included	Not included
Receiving water quality model	Dynamic model included	Steady state model included

In this same light, the continuous simulations of the simplified model can be used to predict the number or frequency of overflow events that may occur, either under existing conditions or employing a number of abatement alternatives. Overflow occurrences can also be used as a calibration tool in comparing the number of overflows monitored versus those predicted over a period of months or years.

SSWMM can also be used to assist in choosing field monitoring locations. This use may arise where a number of drainage or catchment areas appear equally suited for monitoring based on existing data and field reconnaissance. Some preliminary rainfall-runoff analyses of SSWMM may reveal some obvious catchments worthy of monitoring due to their sensitivity to rainfall, interceptor capacity, or other factors.

Once calibration of SSWMM proves successful, the model can be used to screen the various storage and treatment schemes. Detailed SWMM can then be used to determine gross dimensions of the various abatement facilities by simulating an actual design storm or storms. Detailed SWMM, with its better-defined rain events, will produce more accurate peak flow rates and overflow volumes than result from SSWMM.

If a good correlation is found between the predicted outputs of both the detailed and simplified models, more emphasis can be placed on the less complex model for additional screening of alternatives. Detailed SWMM can then be used for final sizing of facilities and for interceptor analyses. Analysis of interceptor sewer systems can be a very important aspect of the total CSO investigation, particularly when dry-weather wastewater treatment facilities are being considered for treating additional wet-weather volumes or when the amount of undiverted flow reaching the interceptor system is affected by surcharging.

DESIGN CONSIDERATIONS FOR QUANTITY PROJECTIONS

The choosing of a design storm or storms is an important consideration in determining the quantity of overflow in the sewer system modeling program. There are several approaches to choosing design storms and there is no one method best suited for all applications. The two common approaches are: (a) long-term, continuous simulation, and (b) the single-event design storm. Both approaches have certain advantages and disadvantages as discussed below.

Continuous Simulation

Continuous simulation offers a major advantage by utilizing actual rainfall data in the CSO analysis for both projecting pollutant loadings and testing abatement alternatives. Level II models all employ continuous rainfall simulation.

Continuous simulation, however, is often more costly to run than a single-event model, particularly if the model employed is moderately complex and several years of data are used. However, to estimate annual or seasonal loadings, long-term rain data employed in conjunction with a calibrated model will give reasonably accurate results. Also, continuous rainfall simulation is an excellent method for estimating the seasonal or annual pollutant reductions from various storage-treatment alternatives. When a lake or slow-moving receiving water is under study, seasonal or annual loadings are important considerations, in addition to the loadings for a single design storm.

Single-Event Design Storm

The single-event design storm has been used for a number of years in stormwater analyses, particularly in the design of storm drainage facilities. Data on rainfall-frequency-duration is usually obtained from the Rainfall Frequency Atlas of the United States (25). This atlas includes rainfall for a number of durations and frequencies, ranging from 5 minutes to 24 hours duration and recurrence frequencies of 1 to 100 years. However, neither the atlas nor hourly rainfall data gives the detailed temporal distribution of rainfall during the course of a rainstorm. If such distribution is needed or desired, as is the case for Level III single-event modeling, synthetic hyetographs are employed.

The synthetic hyetograph has the advantage of applying a storm at the desired duration, return period frequency and average intensity, while incorporating the statistically-determined intensity distribution. Synthetic hyetographs can be developed for any area where sufficient rainfall records are available. The concept is based on the theory that rain falling in a geographical area will fit into a pattern that can be described mathematically. The key elements of a synthetic hyetograph are the volumes of rain falling before the peak, after the peak, and the location of the peak intensity period itself. One of the first papers on the concept was published in 1957 by two City of Chicago engineers (26). An example of a synthetic hyetograph for Syracuse, New York, developed for a number of return periods is shown in Figure 11. The storm duration used with the synthetic hyetograph, or any similar design storm, is usually equal to the time of concentration of the drainage area under consideration.

There have been some recent studies and criticisms of the synthetic hyetograph approach for design storms (27, 28). Some apparent drawbacks stem from the potential for over-predicting of peak flow rates because of

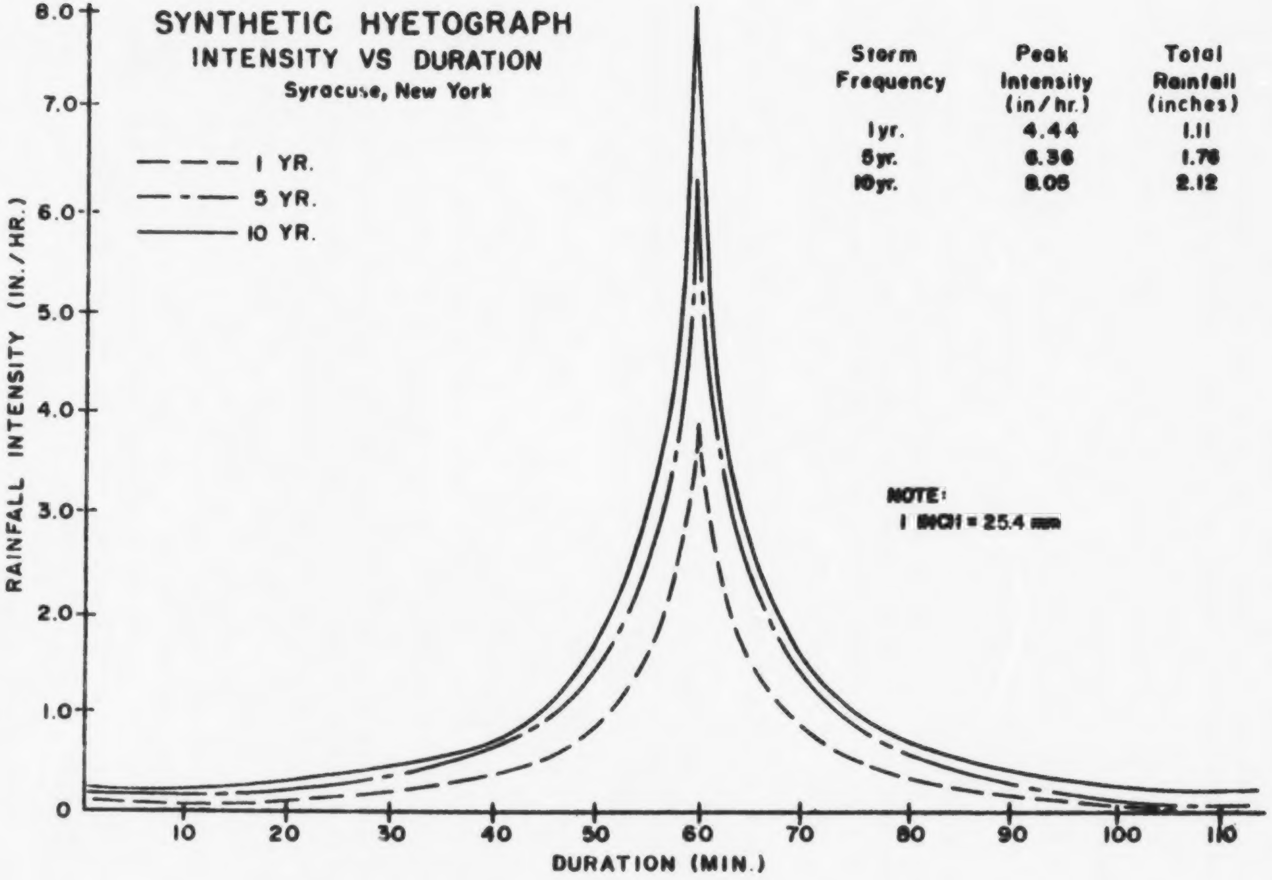


Figure 11. Synthetic hyetograph for Syracuse, New York (6).

the high peak intensities resulting from the development of the synthetic hyetograph. Care must therefore be taken to ensure that the hyetograph is simplified enough, through averaging of time increments, so as not to overpredict peak overflow rates. Sensitivity analyses of various time increments are recommended when employing the synthetic hyetograph for design purposes.

Other Techniques

Routines for the statistical analysis of rainfall data are sometimes incorporated in stormwater models. Such is the case for SSWMM, the Illinois Urban Storm Runoff Model (IUSRM), and the Level I Areawide Assessment Procedures Manual (7, 22, 24). These statistical routines, which can be used separately or in conjunction with the models, allow the user to analyze and select rainfall volumes, durations, intensities and antecedent dry-weather conditions that are either representative or occur at a frequency of return best suited for the particular CSO analysis.

Another method is to reduce long-term rainfall data to a statistically representative period of time. This approach, which is referred to as "annual averaging", was used in the Onondaga County CSO study where over 20 years of rainfall data were reduced through random selection techniques to a two-year period of record for use in SSWMM.

Other possibilities include using a synthetic hyetograph for actual design of a facility, with continuous rainfall simulation employed to test the pollutant-removal effectiveness over the course of a season or a year. This complementary usage offers the advantages of both continuous simulation and the single-event design storm.

When an analysis has multiple objectives, such as for CSO pollution abatement and flood protection, it may be desirable to apply a variety of design storms in conjunction with continuous simulation. For example, design considerations for water quality objectives require an annual loading determination whereas flood protection usually is based on an infrequently occurring storm. For situations where water quality is the prime objective, it is desirable to project loadings for a number of storms with various return periods. The results of these projections can be used to assess the cost effectiveness of the return period selected for the design storm, as will be discussed later in greater detail.

DESIGN CONSIDERATIONS FOR QUALITY PROJECTIONS

There are a number of factors affecting the quality of stormwater runoff and combined sewer overflows. Eight of the more important factors are presented in Table 5.

TABLE 5. FACTORS AFFECTING CSO QUALITY

Antecedent Dry Weather	Affects amount of pollutants available on surfaces and in sewers, and sets initial infiltration capacities of previous surfaces.
Land Use of Catchment Area	The type of land use can dramatically affect the pollutant accumulation rates in an area.
Pollutant Accumulation and Washoff	Accumulation is dependent on antecedent dry weather, land use, street sweeping practices and rainfall characteristics. Pollutants are often modeled as fractions of the amount of dust and dirt.
Street Sweeping Practices	Affects the amount of solids on the streets which is available for washoff.
Soil Erodibility and Erosion Control Practices	Erosion is a source of solids in combined sewers.
Dry Weather Wastewater	Determines the background quantity and quality within an area.
Solids Deposition and Scour in Sewer System	Dependent on antecedent dry weather, sewer system characteristics and rainfall characteristics.
Sewer System Characteristics	Slope, shape and size affect solids transport and deposition.

Historically, quality models have been more difficult to calibrate than quantity models, for a number of reasons. First, many of the components of quality listed in Table 5 are not fully understood, or at least are not yet able to be modeled mathematically in an effective manner. Pollutant accumulation and washoff, erosion and erosion control, solids deposition and scour, effects of antecedent dry weather, and the mechanisms of the "first flush" are all complex phenomena that do not lend themselves readily to either simple field measurements or mathematical relationships. Second, a relatively large amount of monitoring is required to develop the necessary quantity-quality or rainfall-overflow relationships because of the large variability of CSO and stormwater quality data. Although not simple tasks, the hydrologic aspects of rainfall and runoff and the hydraulic aspects of sewer networks are more susceptible to quantification and calibration with a smaller number of monitored storms than are the quality aspects. Third, while quantity lends itself to continuous monitoring, quality does not. Moreover, the parameters of concern in receiving water analysis may be seasonal in impact, thus reducing the possible monitoring period. Examples of seasonal parameters are fecal coliforms, when contact recreation is a goal, and dissolved oxygen, when fish propagation is desired.

One of the objectives of monitoring overflow quality is to develop relationships between each drainage area's rainfall and runoff and pollutant loading rate. Since it is not feasible to collect data at all of the CSO locations for an unlimited number of storms, representative drainage areas are monitored for a few storms in the hope of capturing an adequate variety of rainfall-runoff conditions for projection purposes. The data must be analyzed statistically to determine if there is any correlation between runoff quantity and quality. If a good correlation exists, the resulting relationships can be used for predictive purposes with a relatively high degree of confidence.

On the other hand, adequate data may not exist to develop any meaningful correlation between runoff quantity and quality. Literature quality data should only be used as a last resort, and then only for a very rough assessment, since conditions may vary considerably from one local area to another. It is desirable, at least, to obtain runoff quality data for a small number of rain events since this local data may reveal atypical runoff quality. If the data is within the normal or average values for a particular land use, then the use of literature data can be used with a higher degree of certainty for preliminary assessments.

Pollutant Characteristics

The actual water quality parameters which should be measured in stormwater overflow studies will vary and will depend upon the overall objectives of the analysis, the uses of the receiving water, and the quality aspects of the receiving water, both existing and projected. The next section of this report discusses modeling of the receiving water in detail.

The modeling of pollutants in sewer systems has not progressed to the same state of development as hydrologic and hydraulic simulations. Pollutant parameters commonly modeled include BOD, suspended solids, settleable solids, and coliform bacteria. Nutrients, such as nitrogen and phosphorus, are also included in some models along with a number of other conservative substances; when the receiving water is a lake, nutrients can be particularly important because of their effect on algal growth. A common mechanism used to model pollutant washoff and subsequent routing through the sewer system consists of applying certain fractions, by weight, of a particular pollutant to the solids characteristic of the overflow. The simpler models employ statistical methods based upon land use, population densities, curb length, average rainfall parameters, and other factors.

Characterizations of the overflow pollutants, along with total and peak flow rates, are used to design storage and treatment facilities. Solids and organic loadings and disinfection requirements are all important considerations in the design of such facilities. An important consideration of overflow quality is the "first flush". The "first flush" usually contains the highest concentrations of a number of contaminants and its characterization is an important factor in abatement planning. It may be feasible to capture the "first flush" in storage and/or treatment facilities and substantially reduce the overall pollutant load on the receiving water. The location of the "first flush" relative to the total overflow will assist in the sizing of the abatement facility in a cost-effective manner.

CSO MODELING FOR ONONDAGA COUNTY

Figure 2 shows the steps employed in the sewer system modeling phase of the CSO abatement program for Onondaga County. As stated previously, both detailed SWMM and SSWMM were used in that analysis.

The first step was to develop the necessary sewer and drainage area maps from the Infiltration/Inflow Analysis and other pertinent sources. From these maps, CSO monitoring stations were chosen, based upon drainage area size and other characteristics. Rain gages were installed along with the flow metering and water quality sampling equipment. Overflow quantity and quality were then monitored for a number of storms. Overflow quantity was analyzed in relation to rainfall for all of the monitoring sites. Least-squares fits of rainfall versus total overflow were developed for each area monitored as shown in Figure 12. The individual drainage areas were then composited to develop the total system overflow-rainfall relationship shown in Figure 13.

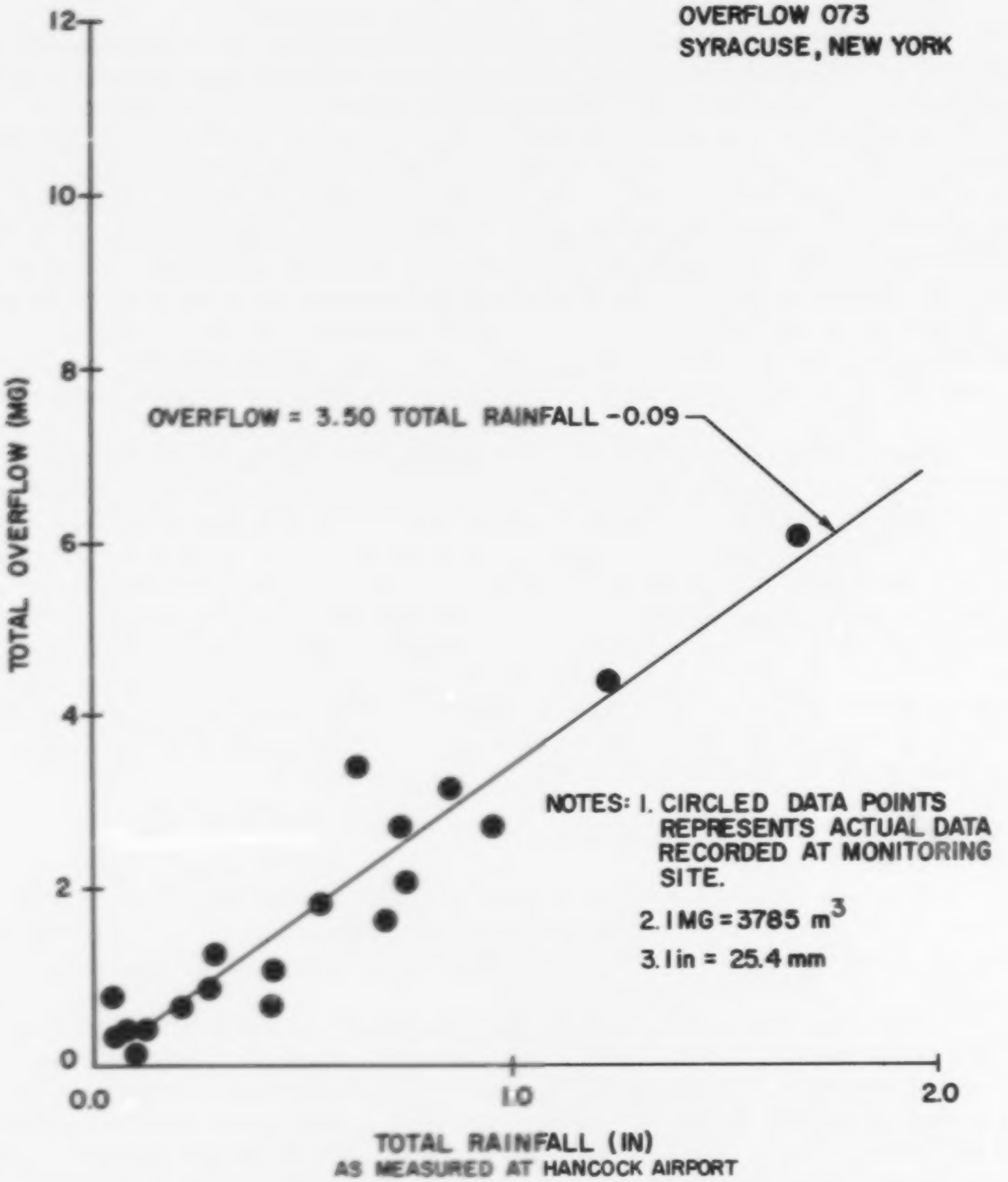


Figure 12. Typical correlation between total rainfall and total overflow for an individual drainage area (6).

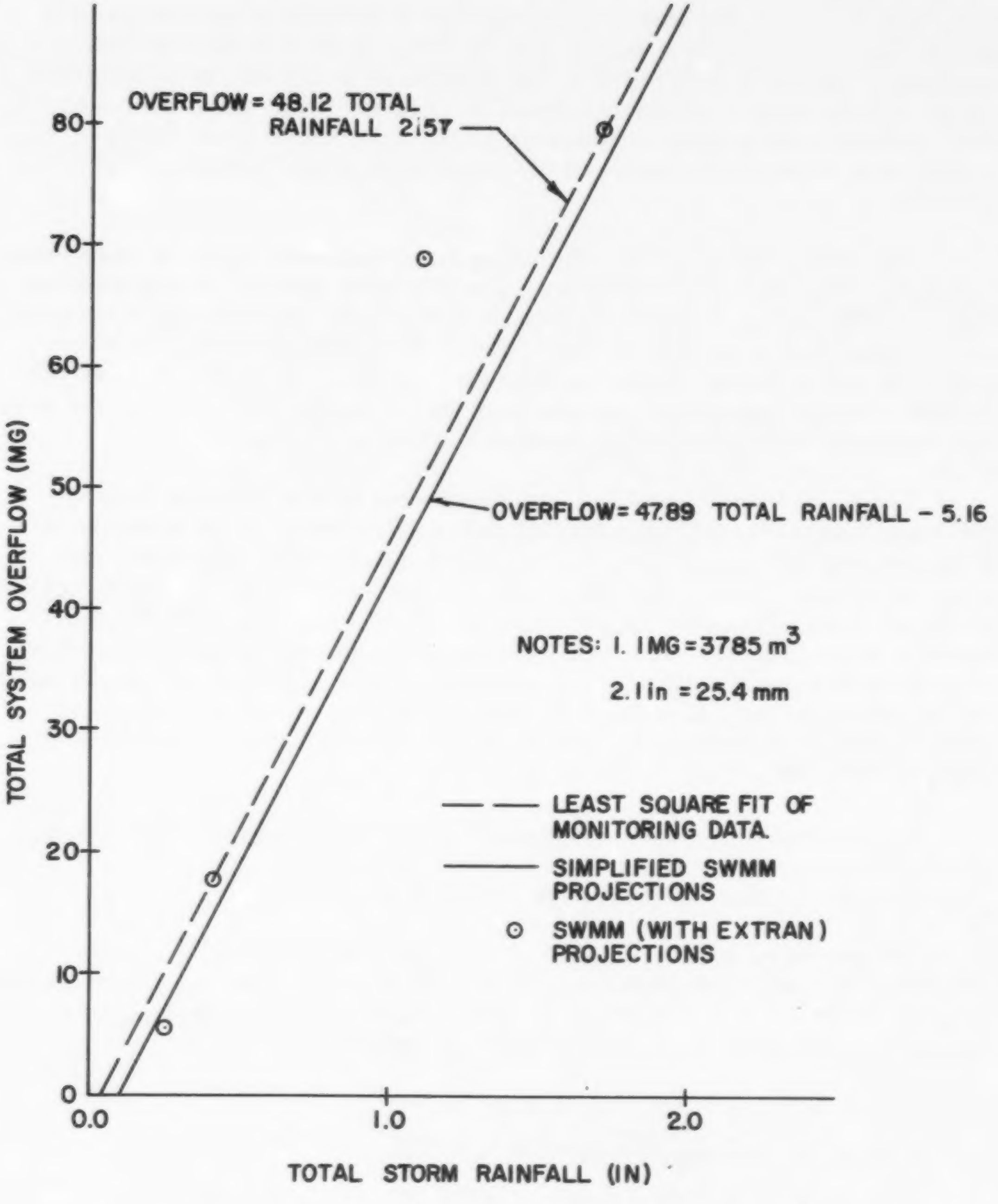


Figure 13. Comparison of SWMM and SSWMM output to measured data for Onondaga County, New York (6).

SSWMM was used to predict total system overflow volumes and to develop and screen preliminary storage and treatment alternatives. The model was calibrated by a mass balance of the total system overflow volumes (Figure 13). SSWMM is not capable of predicting peak overflow rates; hence, only total volume could be used for calibration purposes. Also, SSWMM could only be operated in the daily mode since a linked system was employed because of the large size of the Syracuse CSO network.

The entire CSO system, including the interceptor system, was later modeled, using detailed SWMM with the EXTRAN option. The predicted output of SWMM for a small number of independent storms was compared to both quantitative outputs of SSWMM and the monitored data, as shown in Figure 13. Although good correlation was found to exist, the detailed SWMM results showed that surcharging was a significant factor in the overflow volumes, thus precluding further SSWMM analyses.

The long-term rainfall records collected by the National Weather Service at Hancock Field were analyzed in addition to the data gathered from several rain gages placed in the study area. The long-term data were compared to the data collected from the study area. It was found that the local data correlated closely with the 20 years of National Weather Service data. For use with SSWMM, the 20-year record was reduced to two years of random rainfall. This random two-year data set was found to be equivalent to the 20 years of record at Hancock Field after applying a random selection technique. This process also reduced the operational costs of SSWMM.

In addition to the development of the random two-year data set, a synthetic hyetograph was developed for the area, as shown in Figure 11. This hyetograph was developed for use in detailed SWMM.

To arrive at pollutant loadings, the Onondaga County CSO plan employed statistical analysis in conjunction with the calibrated quantitative models of SWMM and SSWMM. Pollutant loadings were expressed as functions of rainfall through the following equation:

$$\text{Quality} = CbI^{m}$$

where Quality = loading of pollutant in lbs (kg)

C = geometric mean of pollutant, in lb/MG (kg/m^3)

b = intercept of total system overflow in MG (m^3) (see Figure 14)

m = slope of overflow curve (see Figure 14)

I = total rainfall in inches (mm)

This relationship was developed for BOD, TSS, NH_3N, TIP, OrgN and UOD. Table 6 shows the geometric mean pollutant concentration for five of these parameters in relation to two of the area's receiving waters.

TABLE 6. GEOMETRIC MEAN CONCENTRATIONS OF POLLUTANTS ENTERING ONONDAGA CREEK AND LEY CREEK FROM COMBINED SEWER OVERFLOWS

	Onondaga Creek	Ley Creek
BOD, lb/MG (kg/m^3)	505 (0.29)	230 (0.13)
TSS, lb/MG (kg/m^3)	2085 (1.21)	1530 (0.89)
NH_3N, lb/MG (kg/m^3)	20.7 (0.012)	2.5 (0.0015)
TIP, lb/MG (kg/m^3)	2.6 (0.0015)	1.2 (0.00070)
OrgN, lb/MG (kg/m^3)	11.5 (0.0067)	6.5 (0.0038)

Loading curves were then developed for varying return period storms, using the preceding equation and the values contained in Table 6. Figure 14 illustrates a loading curve for BOD_5 discharged into Onondaga Creek.

Once the two models were calibrated, the rainfall and quality data analyzed, and the loading curves developed, the prediction phase was initiated. Quantity and quality responses were simulated for a number of storm conditions. The results of these simulations were entered in the receiving water quality model to assess water quality impact. From these analyses, the required levels of abatement were determined. SSWMM was initially employed to screen the various pollutant removals. Best management practices, in addition to structural alternatives, were considered in the overall abatement planning. Detailed SWMM was used to better define the predicted volumes, determine the output hydrographs, including peak flow rates, and to further screen and select abatement alternatives. These procedures are considered further in the following sections of this report.

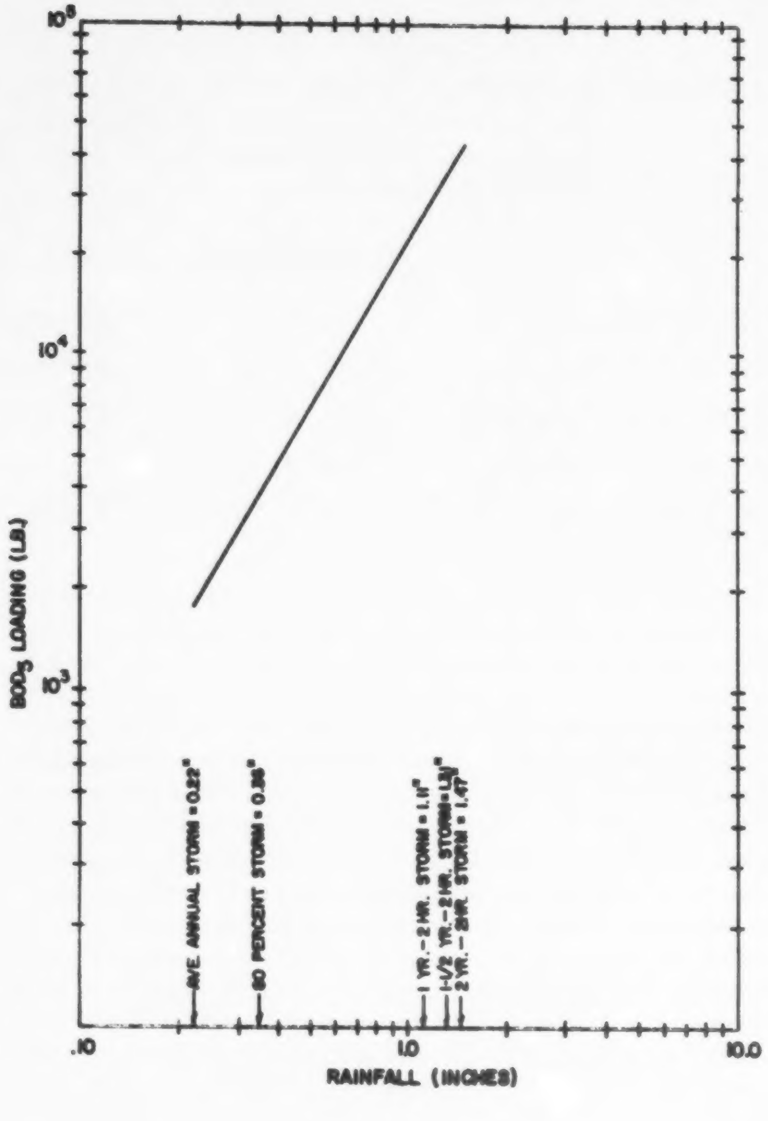


Figure 14. Total BOD_5 load discharged from the combined sewer system to Onondaga Creek for storms of various return periods (6).

SECTION 8

MATHEMATICAL MODELING OF RECEIVING WATER

It is impractical to design a sampling program with the expectation of monitoring a storm which borders on contravention of a particular water quality standard. The probability of monitoring such a storm under critical environmental conditions is even more remote. Therefore, the determination of the allowable pollutant discharge under these conditions requires a predictive tool. Mathematical water-quality models provide such a tool. A mathematical model is defined as an expression or series of expressions which describe the cause-and-effect relationships of a real event. Specifically, water quality models describe the influence of pollutant discharges o receiving waters. Many receiving water models exist; they may be selecte or adapted to accommodate wide variations in level of effort.

The type of model employed in predicting pollutant impact on a receiving water is dependent on several factors: parameters of concern, time frame, desired accuracy of prediction, and project scope. The first two factors are interrelated, since the selection of parameter to be modele generally sets the time frame of the model, an example being the modeling of dissolved reactive phosphorus. If the desired end product is merely to predict phosphorus concentrations within a lake, a steady state model can be employed using annual loads; if the response of algal biomass to dissolved reactive phosphorus concentrations is desired, however, then a dynamic model which incorporates algal nutrient uptake on a continuous basis is required. Figure 15 illustrates parameters as they relate to time. Figure 16 shows interrelationships between sampling and modeling.

PRELIMINARY APPROACH

The seven parameters shown in Figure 15 are commonly related to combined sewer overflows and should be considered in all CSO programs. O these seven, three are commonly modeled for water quality impact; namel bacteria, dissolved oxygen, and nutrients. As previously discussed, nutrients generally can be appraised on a long-term basis (e.g., average annual load) and a steady state model may be appropriate. For bacteria ar dissolved oxygen, however, the time frame of concern is much shorter an may require a dynamic or time-variable approach. In any event, a simple

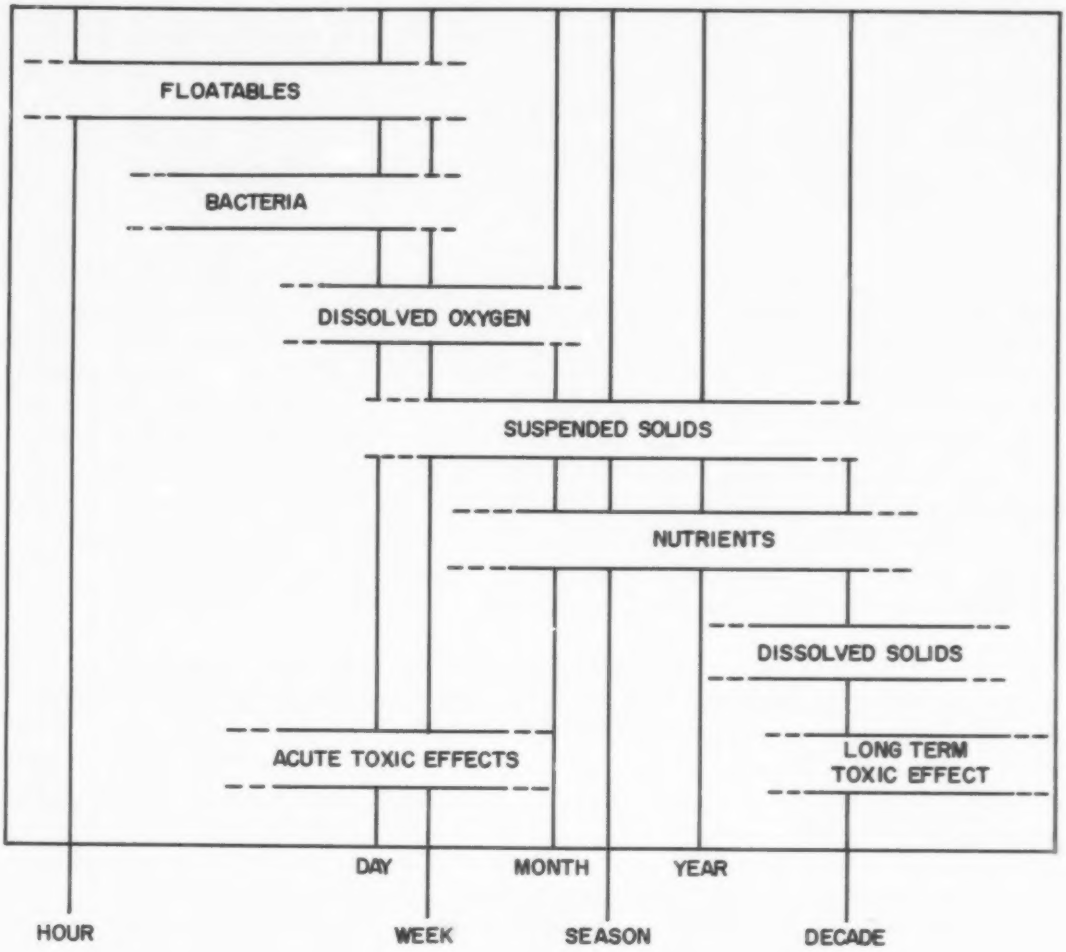

FLOATABLES
BACTERIA
DISSOLVED OXYGEN
SUSPENDED SOLIDS
NUTRIENTS
DISSOLVED SOLIDS
ACUTE TOXIC EFFECTS
LONG TERM
TOXIC EFFECT
DAY
MONTH
YEAR
HOUR
WEEK
SEASON
DECADE

Figure 15. Time frame of concern for various water-quality parameters.(7).

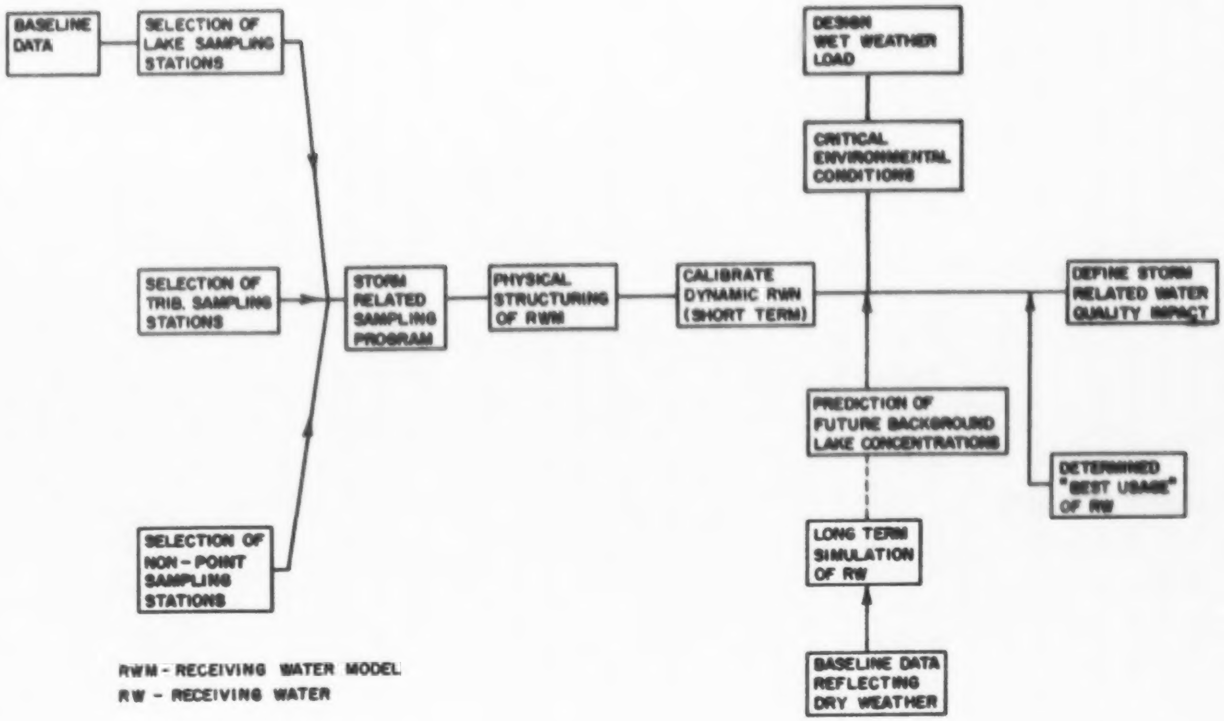

BASELINE DATA
SELECTION OF LAKE SAMPLING STATIONS
SELECTION OF TRIB. SAMPLING STATIONS
SELECTION OF NON-POINT SAMPLING STATIONS
STORM RELATED SAMPLING PROGRAM
PHYSICAL STRUCTURING OF RWM
CALIBRATE DYNAMIC RWM (SHORT TERM)
DESIGN WET WEATHER LOAD
CRITICAL ENVIRONMENTAL CONDITIONS
PREDICTION OF FUTURE BACKGROUND LAKE CONCENTRATIONS
LONG TERM SIMULATION OF RW
BASELINE DATA REFLECTING DRY WEATHER
DEFINE STORM RELATED WATER QUALITY IMPACT
DETERMINED "BEST USAGE" OF RW
RWM - RECEIVING WATER MODEL
RW - RECEIVING WATER

Figure 16. Development of predictive water quality model.

preliminary approach should be taken initially to determine the severity of the problem.

Since the worst case of water quality impact involves transport of an undispersed, potentially critical, pollutant load directly to a recreational area, this case should be evaluated first. If no adverse impact is found under these conditions, one will not occur under less severe conditions. The following steps can be taken to make such a preliminary estimate:

1. Since transport is one of the most important factors affecting water quality, the selection of a realistic current speed is essential to water quality predictions. Long-term current measurements generally are not available for most lakes; therefore, a current speed for predictive purposes must be derived from another source. Since the primary force affecting currents is wind speed and direction, historical wind records can be analyzed to determine under some predefined criteria a critical wind speed. If a correlation between wind vectors and current vectors can be made by monitoring both vectors over a short time period, then the critical wind speed can be converted to a critical current.

2. Segment the lake so that any actual multi-dimensional flow can be viewed as a one-dimensional water body (i.e., river). As shown in Figure 6, rather than having Cell 1 flow to both Cells 2 and 3, treat the flow as if it hugs the shore and does not interact with the mid-lake segments.

3. Compute a mass balance for a critical cell (Cell 1, as shown in Figure 6) using the maximum concentration anticipated from the combined sewer overflows and the mass transfer of water throughout the lake associated with the maximum current velocity determined in Step 1. Since the continuity equation ($Q = AV$) applies, this flow can be computed as the product of the average velocity times the cross-sectional area of the interface between adjacent cells (e.g., Cells 4 and 1). The concentration of pollutant in a given volume of water passing through Cell 1 can then be computed as follows:

$$C_1 = \frac{Q_{lake}(C_{lake}) + Q_{load}(C_{load})}{Q_1}$$

where C_1 = concentration of pollutant in Cell 1

Q_1 = flow leaving Cell 1 = $Q_{lake} + Q_{load}$

Q_{lake} = flow across the interface between Cells 4 and 1

C_{lake} = in-lake concentration of pollutant entering Cell 1

Q_{load} = flow associated with combined sewer discharges

C_{load} = concentration of pollutant associated with combined sewer discharges

4. In the case of a non-conservative pollutant, an estimate of reaction rate must be obtained either from the literature or from special ecosystem studies. For example, if the parameter under consideration is bacteria, the literature contains a wide range of data on bacterial die-off (31). The most conservative case should be utilized; for bacteria it would be the minimum die-off rate. Critical conditions are discussed in greater detail in Section 9.

5. Knowing the area proposed for recreational uses and the approximate time of travel from the loaded cell (Cell 1) to this area, the natural reduction in non-conservative pollutant loads can be computed. In the case of bacterial die-off and BOD-DO relationships, the first order Chick's Law and Streeter-Phelps equations can be used, respectively.

Onondaga County

Using Onondaga Lake as an example (see Figure 7), the current associated with maximum wind velocity is 0.26 mph (0.12 m/sec), the area of the interface between Cells 1 and 2 is 25,400 ft^2 (2360 m^2), and the load associated with combined sewer discharges is 2.3 x 10^{16} cells per day. The time of travel between the loaded cell (Cell 1) and Cell 11 is approximately 0.4 days, and the bacterial die-off rate is 1.16 per day. This die-off rate was determined through laboratory measurements of Onondaga Lake water. Using the above step-by-step approach, the concentration expected in the recreational zone (Cell 11) was calculated to be 5.4 x 10^4 cells/100 ml. Since this preliminary approach yielded concentrations in the recreational zone exceeding the allowable standards for its classification (200 cells/ 100 ml), a more detailed evaluation was required. However, had this initial procedure yielded concentrations which met standards for the intended best usage of the water, it would have sufficed and resulted in significant cost savings.

A similar approach generally can be employed for dissolved oxygen using an expanded form of the Streeter-Phelps equation; in the case of Onondaga Lake, however, this method was not practical because of the influence of fluctuating algal biomass which masked the BOD-DO relationships.

DETAILED MODEL

The model (29) developed in this section describes the three-dimensional transient distribution of fecal coliform, total phosphorus, BOD and dissolved oxygen in Onondaga Lake following stormwater overflow events from the City of Syracuse. The model includes advective and dispersive transport and mechanisms for settling, scour, and chemical and biochemical reaction.

Advective transport is the transfer of mass between adjacent volumes of water as a result of the unidirectional flow, whereas dispersive transport actually mixes adjacent volumes of water as a result of the mass gradient of a particular constituent (30). Figure 17 presents a visual distinction between an advective and an advective-dispersive transport system. For simplicity, the figure depicts a slug discharge of a non-conservative substance to a one-dimensional body of water and shows both the slug traveling intact with the flow (advective transport) and the spreading of the slug as it proceeds downstream with the flow (advective-dispersive transport). The simplified "preliminary approach" previously presented treats the system as if advective were the only transport mechanism, whereas in actuality the maximum concentration will be further diminished by dispersion. Figure 17 shows that pollutant concentration is the maximum under a purely advective condition. The potential sources and sinks of pollutant concentration are presented in Figure 18.

Most of the material presented under "Detailed Model" has been quoted or paraphrased directly from Limno-Tech, Inc., (29).

The model is based on the conservation of mass as expressed by the following equation:

$$\text{Accumulation of Mass} = \text{Net Input of Mass from Advective Transport} + \text{Net Input of Mass from Dispersive Transport} \pm \text{Sources and Sinks of Mass}$$

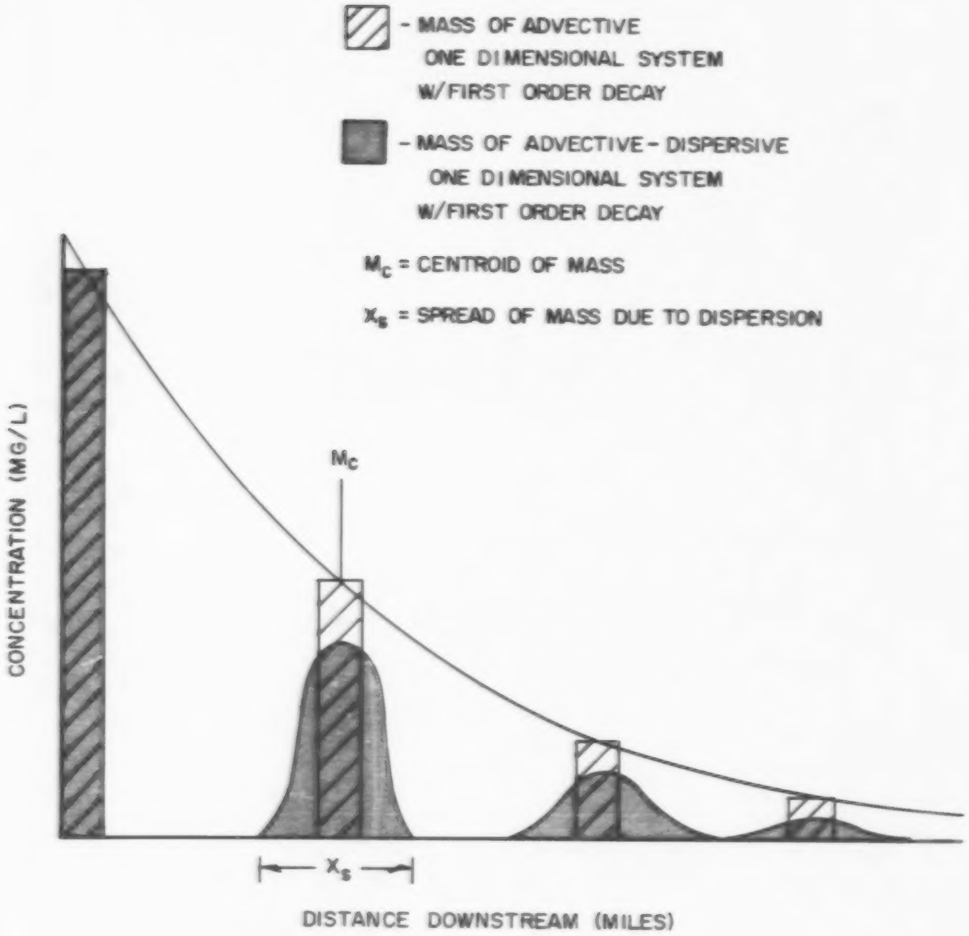

▨ - MASS OF ADVECTIVE ONE DIMENSIONAL SYSTEM W/FIRST ORDER DECAY
■ - MASS OF ADVECTIVE - DISPERSIVE ONE DIMENSIONAL SYSTEM W/FIRST ORDER DECAY
M_c = CENTROID OF MASS
X_s = SPREAD OF MASS DUE TO DISPERSION
CONCENTRATION (MG/L)
M_c
X_s
DISTANCE DOWNSTREAM (MILES)

Figure 17. Comparison of the effects on concentration of advective and advective-dispersive transport.

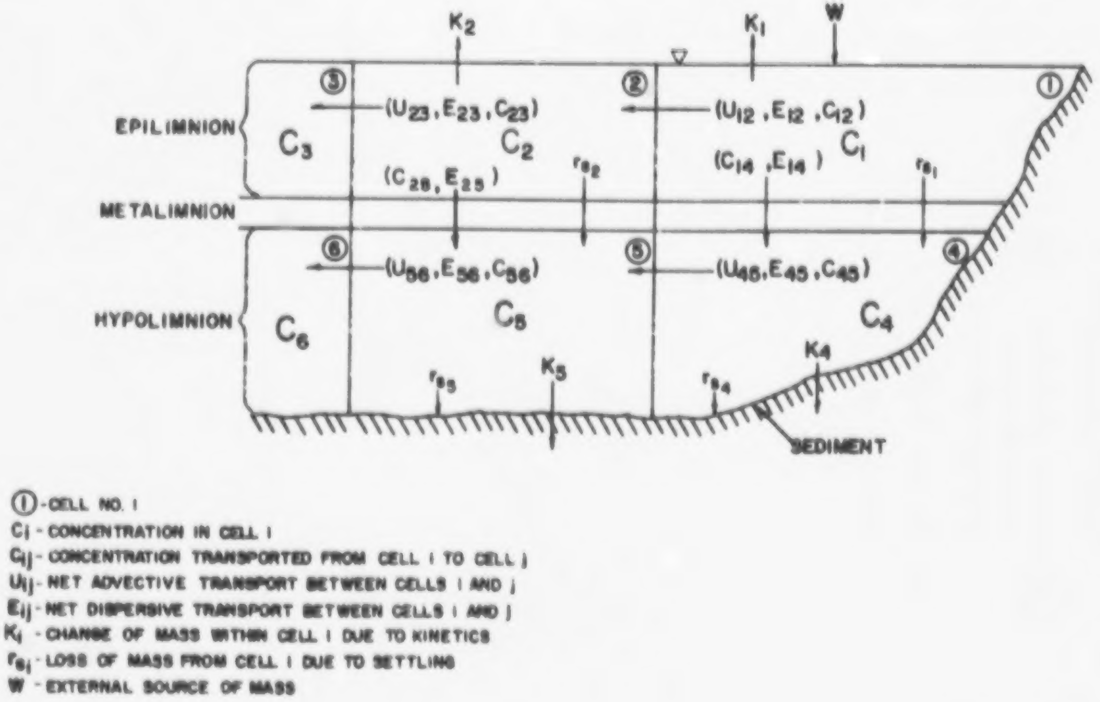

K2
K1
W
③
②
①
(U23, E23, C23)
(U12, E12, C12)
EPILIMNION
C3
C2
C1
(C25, E25)
(C14, E14)
rs2
rs1
METALIMNION
⑥
⑤
④
(U56, E56, C56)
(U45, E45, C45)
HYPOLIMNION
C6
C5
C4
K4
rs5
K5
rs4
SEDIMENT
①-CELL NO. I
Ci - CONCENTRATION IN CELL I
Cij - CONCENTRATION TRANSPORTED FROM CELL I TO CELL J
Uij - NET ADVECTIVE TRANSPORT BETWEEN CELLS I AND J
Eij - NET DISPERSIVE TRANSPORT BETWEEN CELLS I AND J
Ki - CHANGE OF MASS WITHIN CELL I DUE TO KINETICS
rsi - LOSS OF MASS FROM CELL I DUE TO SETTLING
W - EXTERNAL SOURCE OF MASS

Figure 18. Forces acting on a pollutant mass discharged to a two-dimensional advective-dispersive system.

or mathematically
$$\frac{\partial C}{\partial t} = \nabla . E \nabla C - \nabla . UC + r$$

where C = concentration of pollutant (mg/l)
t = time (days)
E = dispersion coefficient (m^2/day)
U = velocity (m/day)
r = reaction sources or sinks (mg/l/day)

Since a direct solution of this equation is usually not possible, the solution requires the use of approximate solutions. The finite difference solution, which is equivalent to representing the continuous lake system as a collection of completely mixed cells that are interconnected by advective and dispersive transport, was used in this model. This approach does sacrifice some spacial accuracy; however, the careful segmentation of the water body to closely represent the overall circulation and mixing minimizes these inaccuracies. Consistent with the above approach, the model treats the lake as two vertical layers with 21 interconnected horizontal segments in the epilimnion and six interconnected horizontal segments in the hypolimnion (Figure 7). Measurements from U.S. Lake Survey Chart No. 180 were analyzed and used to define the morphology of Onondaga Lake and to establish the dimensions of each model cell.

The model utilizes steady-state circulation patterns and hydraulic loads and time-variable pollutant loads to simulate the lake's water quality response to stormwater discharges. The model linearly interpolates the transient pollutant loadings from tabular input data to formulate the pollutographs discharging to each model cell. Time-varying changes in flow associated with stormwater input are normally small in comparison with dispersive and advective flow of the lake circulation pattern; therefore, the use of steady-state hydraulic loads was considered applicable. The assumption of steady-state in-lake hydraulics may, however, be invalid for major changes in lake circulation patterns caused by fluctuations in wind during the period of simulation. These variations in lake hydraulics can be roughly simulated by using stepwise changes in steady-state hydraulic patterns whenever a marked change in current is required.

Fecal Coliform Model Kinetics

In addition to the simulation of the transport of bacteria (fecal coliform) throughout the lake, the model accounts for the loss of organisms due to die-off and settling. The die-off term encompasses the reduction of bacterial numbers as a result of protozoan predation, sunlight disinfection, natural death and respiration. Regrowth of fecal coliform in Onondaga

Lake was assumed negligible. The overall die-away rate is represented in the model by Chick's Law:

$$r_f = k_f(N)$$

where r_f = rate of fecal coliform die-away (cells/l/day)

k_f = die-away coefficient (day^{-1})

N = fecal coliform concentration (cells/l)

The rate of bacterial die-off is dependent on temperature, with the organisms being more persistent at lower temperatures. The die-off rate for coliform bacteria is considered linearly dependent on temperature according to the following equation (32):

$$k_{f_T} = k_{f_{20}} (0.31 + 0.0345T)$$

where k_{f_T} = coliform die-off rate at temperature T (day^{-1})

$k_{f_{20}}$ = coliform die-off rate at 20°C (day^{-1})

T = temperature (°C)

The loss of bacteria from the water column due to settling is described in the following expression:

$$r_{f_s} = \frac{VSF}{D} \times N$$

where r_{f_s} = rate of loss due to settling (cells/l/day)

D = depth (m)

VSF = settling velocity of fecal bacteria (m/day)

N = bacteria concentration (cells/l)

Total Phosphorus Model Kinetics

Total phosphorus was considered to be a relatively conservative substance in which net changes in concentration were limited to settling, sediment release or bottom scour. While only particulate forms of phosphorus settle, the non-settleable soluble organic and soluble reactive forms are converted to settleable material through biochemical processes such as zooplankton grazing and fish predation, and chemical conversion (appatites).

A model which individually describes these complex interactions was well beyond the scope of the Onondaga project; therefore, the model uses a net effective settling velocity for total phosphorus which incorporates the overall removal rate in one term. The following simple kinetic expression is used to describe the rate of phosphorus loss to the sediments and sediment release of phosphorus:

$$r_p = -(VSP/D)P + SBP/D$$

where r_p = overall kinetic rate for total phosphorus (mg/l/day)

VSP = average settling velocity (m/day)

D = depth (m)

P = total phosphorus concentration (mg/l)

SBP = sediment release of phosphorus caused by anaerobic conditions or scour (g/m^2/day)

Dissolved Oxygen Model Kinetics

The dissolved oxygen model includes kinetic expressions describing reaeration, oxidation and settling of carbonaceous and nitrogenous oxygen demand material (CBOD and NBOD), algal photosynthesis and respiration, and sediment oxygen demand (SOD). The following paragraphs describe the model kinetics for each of these processes.

Removal Rates for Organic Components--

CBOD occurs in both the dissolved and particulate forms and the appearance of this material is governed by mechanisms such as settling, sediment scour, stripping, adsorption and biological oxidation. The rate of bacterial oxidation of organic carbon has been traditionally described by first-order kinetic expressions. The model uses such expressions, modified by a non-linear decay coefficient, to account for inhibition of biological oxidation at low dissolved oxygen concentrations (33). In addition to biochemical decay, a physical removal mechanism for settling is used in the model. The overall kinetic term for CBOD is:

$$r_{CBOD} = (k_{c*} + VSC/D)\ CBOD$$

where r_{CBOD} = overall removal rate for CBOD (mg/l/day)

k_{c_*} = non-linear biological oxidation decay coefficient (day^{-1})

VSC = settling velocity of CBOD (m/day)

D = depth (m)

CBOD = carbonaceous biological oxidation demand (mg/l)

NBOD is exerted as a consequence of the bacterial oxidation of ammonia to nitrite to nitrate. Municipal and many industrial wastes contain nitrogenous material in both the organic and ammonia forms, the organic compound of which must be hydrolyzed to ammonia before biochemical oxidation can occur. Autotrophic oxidation of ammonia to nitrite and nitrate has been described by first-order kinetic rate laws. The Onondaga Lake model uses a first-order expression for nitrification with a non-linear modification to account for inhibition of nitrification at low levels of dissolved oxygen (34). The model also uses a first-order expression to describe the settling of nitrogenous material. Both the organic and ammonia forms of nitrogen are present as dissolved and particulate matter. The particulate material, especially organic nitrogen, can settle before it has a direct impact on the lake's dissolved oxygen resources, although ultimately the material will exert a benthal demand. The overall kinetic expression for NBOD is given by the following equation:

$$r_{NBOD} = (k_{N_*} + VSN/D)\ NBOD$$

where r_{NBOD} = overall removal rate for NBOD (mg/l/day)

k_{N_*} = non-linear nitrification decay coefficient (day^{-1})

VSN = settling velocity of NBOD (m/day)

NBOD = nitrogenous biochemical oxygen demand (mg/l)

Biological Deoxygenation--

While the overall removal rate for the organic constituents (CBOD and NBOD) results from a combination of physical (e.g., settling) and biochemical (e.g., bacterial utilization) phenomena, only the biochemical changes have a direct effect on the dissolved oxygen. The settling mechanism indirectly affects the DO by removing oxidizable material from the water column. The oxidizable organic material deposited on the lake bottom ultimately exerts a benthal oxygen demand.

The total deoxygenation rate (r_d) due to the decay of organic matter remaining in the water column is represented by the following equation:

$$r_d = k_{c_*}(\mathrm{CBOD}) + k_{N_*}(\mathrm{NBOD})$$

Benthal Oxygen Demand--

The oxygen depletion rate by organic sediments is considered constant (zero order) with inhibition at low dissolved oxygen concentration. The rate of oxygen demand due to benthal deposits, B, is defined by the following equation:

$$r_b = \frac{B_*}{D}$$

where r_b = oxygen uptake due to benthal demand (mg/l/day)

B_* = non-linear benthal oxygen demand (g/m^2/day)

D = depth (m)

Reaeration--

Dissolved oxygen has limited solubility in water and its presence in adequate concentrations is critical to the preservation of healthy aerobic aquatic communities. Oxygen solubility in water is dependent mainly upon the partial pressure of atmospheric oxygen, temperature and the concentration of dissolved and suspended impurities. The dissolved oxygen saturation concentration is dependent on the temperature and salinity of the water (35).

Any gradient between the oxygen saturation concentration and the actual in-lake oxygen concentration causes the natural forces of gas transfer to act to restore the lake concentration to the equilibrium level. This rate of restoration is called reaeration, r_a, and is described mathematically as:

$$r_a = k_a(DO_S - DO)$$

where r_a = rate of reaeration (mg/l/day)

k_a = reaeration rate coefficient (day^{-1})

DO_S = dissolved oxygen concentration at saturation (mg/l)

DO = in-lake dissolved oxygen concentration (mg/l)

Wind action on the water surface is primarily responsible for reaeration in lake systems. Figure 19 describes the atmospheric reaeration coefficient as a function of wind speed and mixed-layer depth (36).

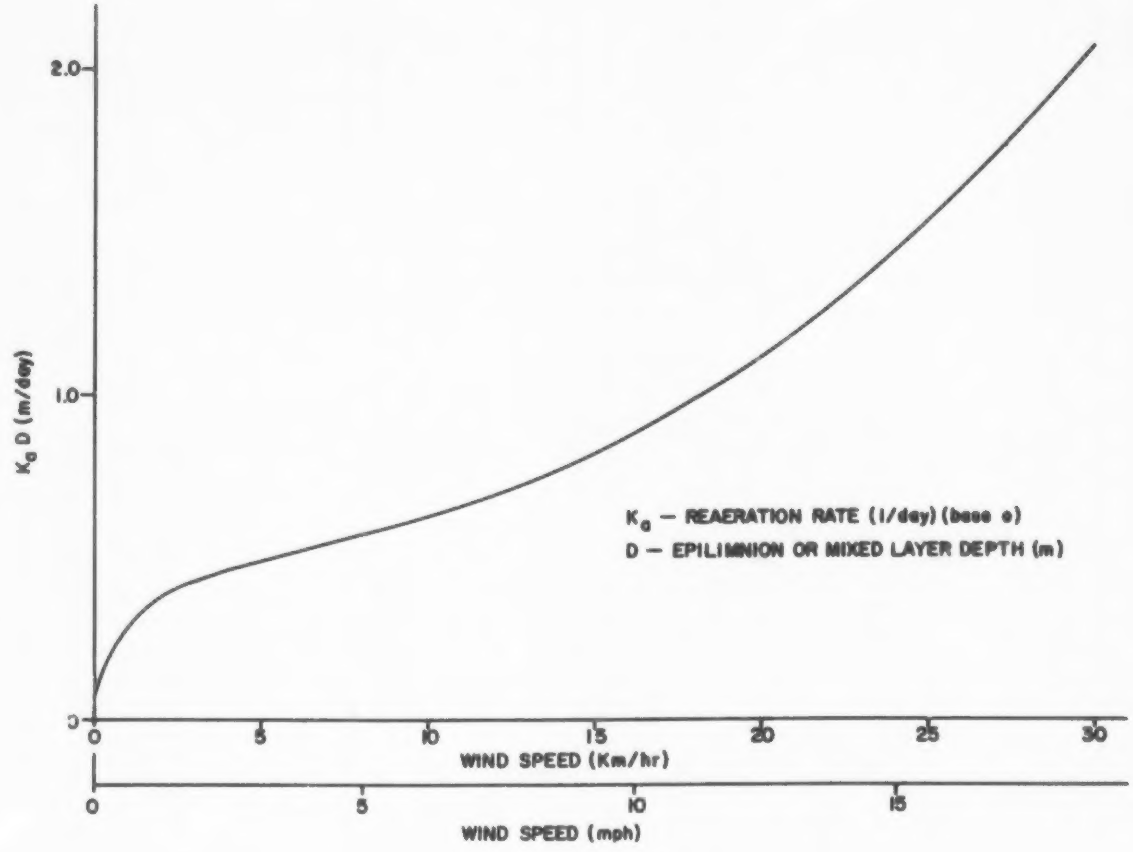


Figure 19. Reaeration rate as a function of wind speed. (36)

Temperature Corrections--

The oxidation rates for the various mechanisms are dependent on temperature and correctable using the modified Arrenhius equation. The basic equation is as follows:

$$k_T = k_{20} \theta^{(T-20)}$$

where k_T = corrected rate coefficient at temperature T (day^{-1})

k_{20} = rate coefficient at 20° C (day^{-1})

θ = rate correction factor dependent on parameter

T = temperature (° C)

The values of θ used in this model are presented in Table 7.

TABLE 7. TEMPERATURE CORRECTION FACTORS (31)

Rate Coefficient	θ
Carbonaceous Oxygen Demand	1.047
Nitrogenous Oxygen Demand	1.09
Sediment Oxygen Demand	1.065
Reaeration	1.024

Net Productivity--

Planktonic algae and rooted macrophytes have both a beneficial and detrimental effect on the oxygen resources of natural water bodies. During periods of sunlight, under favorable nutrient and temperature conditions, macrophytes and algae fix carbon dioxide and produce oxygen through the process of photosynthesis. However, these plants must also constantly oxidize organic matter for energy through the process of respiration. Consequently, during prolonged periods of darkness, algal or macrophyte respiration can seriously deplete the oxygen resources of a lake. While a sophisticated phytoplankton model with nutrient cycles would be very useful for understanding water quality dynamics, the development of this type of model was well beyond the scope of the Onondaga Lake study.

The model does, however, compute the effect of algae on the lake's dissolved oxygen budget. Algal photosynthesis oxygen production is calculated using chlorophyll a, nutrient and incident light measurements according to the following equation (30, 37):

$$r_{photo} = Y(G_{p,L})(G_{p,N})(G_{p,MAX})(\text{Chl } \underline{a})$$

where r_{photo} = photosynthetic production of oxygen (mg/l/day)
Y = mgO_2/mg Chl $\underline{a}$
$G_{p,L}$ = light attenuation and inhibition factor (dimensionless)
$G_{p,N}$ = nutrient limitation factor (dimensionless)
$G_{p,MAX}$ = rate of maximum algal photosynthesis (day^{-1})
Chl $\underline{a}$ = chlorophyll $\underline{a}$ concentration (mg/l)

The model predicts algal respiration using the following equation:

$$r_{resp} = -Y(k_{R_*}) \text{ Chl } \underline{a}$$

where r_{resp} = rate of oxygen depletion due to respiration (mg/l/day)
Y = mgO_2/mg Chl $\underline{a}$
k_{R_*} = non-linear temperature-dependent respiration coefficient (day^{-1})

Overall, the dissolved oxygen kinetics can be described by the sum of all of the individual reaction terms: r_d, r_a, r_b, r_{photo}, and r_{resp}.

In the model, nutrient concentrations and average daily incident light in conjunction with their respective saturation constants (K_N, K_P and I_s) are needed to determine nutrient and light limitations on algal photosynthesis. Lake nutrient and incident light data are linearly interpolated by the model from input data to estimate the nutrient concentrations and incident light at any specific time during a simulation. The algal population is estimated from interpolated chlorophyll $\underline{a}$ concentration data. This information is combined in the model to calculate algal photosynthesis and respiration.

During photosynthesis, algae utilizes carbon dioxide to produce dissolved oxygen. Hence, algal productivity is a source of autochthonous (internal) organic loading to the lake. The autochthonous production of CBOD is included in the model by an addition of a load equivalent to $r_{photo} + r_{resp}$. Because organic carbon is expressed as oxygen in the model, stoichiometric conversion is not required.

MODEL CALIBRATION AND VERIFICATION

The interaction of data collection and mathematical modeling phases of any project occur during the model calibration and verification. While establishment of the general framework of the various sub-models is based on widely-accepted relationships, the particular forcing functions, kinetics and system responses applicable to each body of water must be formulated from the data collected during real storms. The model calibration for Onondaga Lake, for example, was completed initially in the steady-state mode using average yearly pollutant concentrations. Calibration was further refined in the dynamic state using a single storm with minimal interferences. Once the variables were determined from the calibration phase, the model was then verified through data collected during three separate phases.

The lake model requires detailed data input for hydrology, influent loads, circulation, dispersive transport, reaction coefficients, and environmental conditions. Each of these inputs must be specified for every model simulation and projection. The following paragraphs describe each model input required and their source in the case of Onondaga Lake.

Hydrology, Influent Loads, Circulation, Dispersive Transport

Basic to the model is quantification of influent flow and waste loads and measurement of in-lake transport. In the case of Onondaga Lake, all major tributaries were gaged by the U. S. Geological Survey and records were available for all storms. Since the model can only accommodate steady-state hydraulics, an average flow for the entire storm is all that is required. If no stream gages are available, a temporary gage can be established in all major tributaries at a convenient cross section. Periodic measurements with a velocity meter over a range of flows will establish a stage-discharge curve for the particular cross section. Field personnel are thus enabled to obtain flow during the storm by periodically measuring depth; the frequency of measurement will depend on the response time of the particular drainage basin. Pollutant loads can be computed using measured flows and associated concentrations determined through storm sampling.

The in-lake transport can be more critical than the hydraulic load, depending on the morphology of the lake. The circulation of Onondaga Lake during each storm sampling period was determined using velocity measurements taken in both the epilimnion and hypolimnion at the various stations. The individual velocity measurements were then time-averaged to provide an overall velocity at each station; from these velocities the appropriate in-lake circulation patterns (gyre) were formulated. Figure 20 shows a plot of

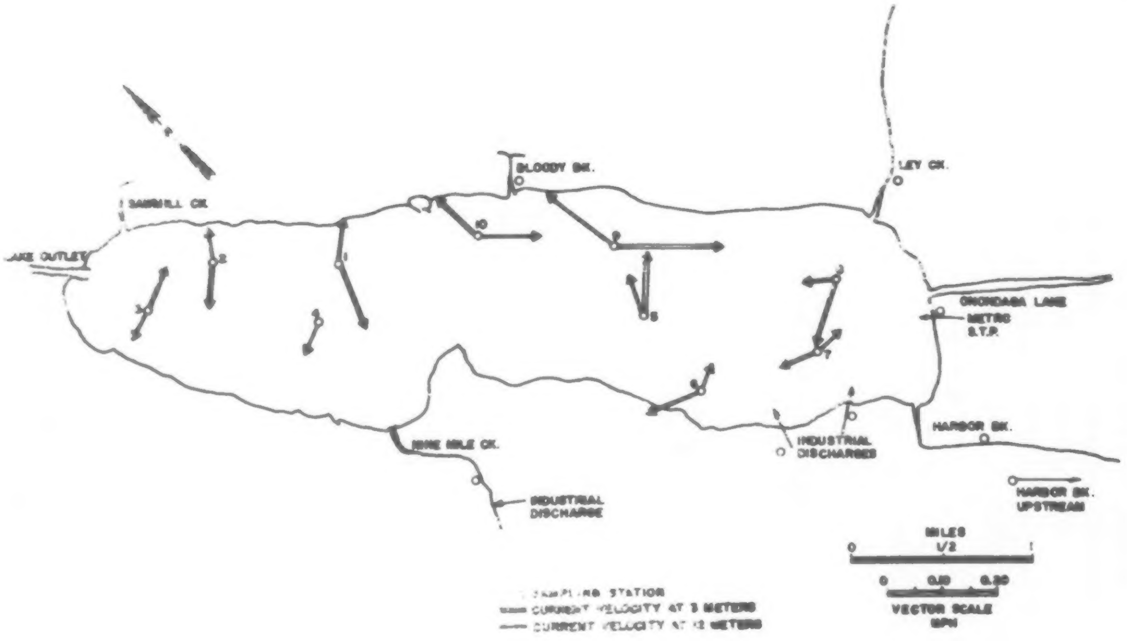

LAKE OUTLET
SAWMILL CK.
BLOODY BK.
LEY CK.
ONONDAGA LAKE
METRO S.T.P.
HARBOR BK.
INDUSTRIAL DISCHARGES
NINE MILE CK.
INDUSTRIAL DISCHARGE
HARBOR BK. UPSTREAM
1
2
3
4
5
6
7
8
9
10
MILES
0
1/2
1
0
0.10
0.20
VECTOR SCALE
MPH
○ SAMPLING STATION
CURRENT VELOCITY AT 3 METERS
CURRENT VELOCITY AT 12 METERS

Figure 20. Individual current measurements.

individual time-weighted velocities (both epilimnion and hypolimnion) from which the circulation patterns were determined. While this pattern, which corresponds to the advective transport within the lake, can be measured directly, the phenomenon of dispersion must be estimated. Initial estimates of dispersion were based on literature values and then refined through model calibration. The dispersion coefficients used in the model are summarized in Table 8.

TABLE 8. DISPERSION COEFFICIENTS (29)

Location	Range of Dispersion Coefficients (cm^2/sec)
Epilimnetic near shore	$2.9 - 4.6 \times 10^3$
Epilimnetic mid-lake	$3.5 - 6.0 \times 10^4$
Epilimnetic basin interface	$4.1 - 8.1 \times 10^4$
Hypolimnetic horizontal	$8.1 - 16.2 \times 10^4$
Hypolimnetic-epilimnetic vertical	5.0×10^{-1}

Reaction Coefficients

Model reaction and settling coefficients were determined by a survey of the literature (31, 38, 39), laboratory measurements (40), and model calibration (29). The coefficients utilized in the Onondaga Lake study are summarized in Tables 8, 9 and 10. As an initial approximation of the deoxygenation coefficient for both carbonaceous and nitrogenous demanding material, analysis of laboratory data was used (40). The reaction rate determined from the laboratory studies proved to far exceed the reaction rates finally determined through calibration of the model. It may have been the result of low dissolved oxygen or the high chemical concentration in the lake, which can limit the biological activity. As previously discussed, the reaeration coefficients were determined as a function of wind speed, based on literature values (36). The relationship between wind speed and reaeration coefficient is presented in Figure 19. The mixed-layer depth in Onondaga Lake during the summer months is 9 meters, and this value was used throughout the study.

The benthal oxygen demand can be measured either through oxygen uptake studies of undisturbed sediment cores or by constructing an oxygen uptake chamber on the lake floor. Due to the difficulty of constructing a chamber, the results of laboratory studies conducted previously (41) were

TABLE 9. REACTION COEFFICIENTS AND SINKING RATES VERIFIED THROUGH MODEL CALIBRATION (29)

Parameter	Reaction Coefficient k_X (day^{-1})*	Sinking Rate - VSX (ft/day)		
		Near Shore	Mid-Lake	Hypolimnion
Fecal Coliform (F)	1.16	0.0	1.97	0.0
Phosphorus (P)	--	0.39	2.95	0.144
CBOD (C)	0.10	0.98	3.28	0.98
NBOD (N)	0.0115	0.0	1.67	0.049

---

*base e @ 20°C

X - designated specific parameter

TABLE 10. DISSOLVED OXYGEN REACTION COEFFICIENTS (29)

Symbol	Coefficient Designation	Reaction Coefficient
k_a	Reaeration Coefficient	*
Y	mgO_2/mg Chl a	266 mgO_2/mg Chl a
I_s	Algal Light Saturation Constant	240 Langleys/day
K_N	Saturation Constant - Inorganic Nitrogen	0.015 mg N/1
K_P	Saturation Constant - Soluble Reactive Phosphorus	0.0025 mg P/1

---

* Varies with wind speed; see Figure 19.

utilized. The benthal demand utilized was 0.5 $mgO_2/m^2/day$. This value is extremely low when compared to other polluted systems (31), but may be associated with the high proportion of inorganics identified in the benthos (41).

Subsequent to the sampling program of this project, a substantial flocculent sediment layer was measured in Onondaga Lake which may exert a greater oxygen demand than the compacted layer sampled with the corer. The oxygen demand of this flocculent layer is currently being investigated.

Environmental Conditions

The environmental factors utilized in computing and correcting reaction coefficients and computing photosynthetic oxygen production and algal respiration for the various model runs are presented in Tables 7 and 10. Wind data, water temperature, secchi disc and algal nutrient concentrations were derived from the monitoring data, and incident light was determined from long-term regional data. However, the incident light was corrected for the percent cloud cover reported by the National Weather Service at Hancock International Airport in Syracuse. Model input of chlorophyll a was derived from limited data and had to be interpolated to provide sufficient temporal data. The data utilized for pre-storm conditions were derived from measurements made during the storm survey.

The calibration process for both the fecal coliform and dissolved oxygen models is outlined in Figures 21 and 22. In order to demonstrate impact, the Onondaga Lake verification plots of the most severe storm loads are presented in Figures 23 through 27. In these figures, the curve predicted by the calibrated water quality model is superimposed on the actual measured data points. Similar fits of model predictions to measured results were obtained for the other three storms monitored, which varied greatly in intensity.

Sensitivity Analysis

In order to determine the relative effects of the various parameters on water quality, sensitivity analyses should be performed on several variables. These analyses should be performed by varying several critical parameters one at a time and observing the change in impact of the model output. The parameters for which these analyses should be performed are: all rate coefficients (i.e., carbonaceous and nitrogenous oxidation coefficients, reaeration coefficients, fecal coliform die-away rates), benthal uptake and algal productivity in the case of DO, and sediment scour and release in the case of nutrients. In general, a 25 to 50 percent plus or

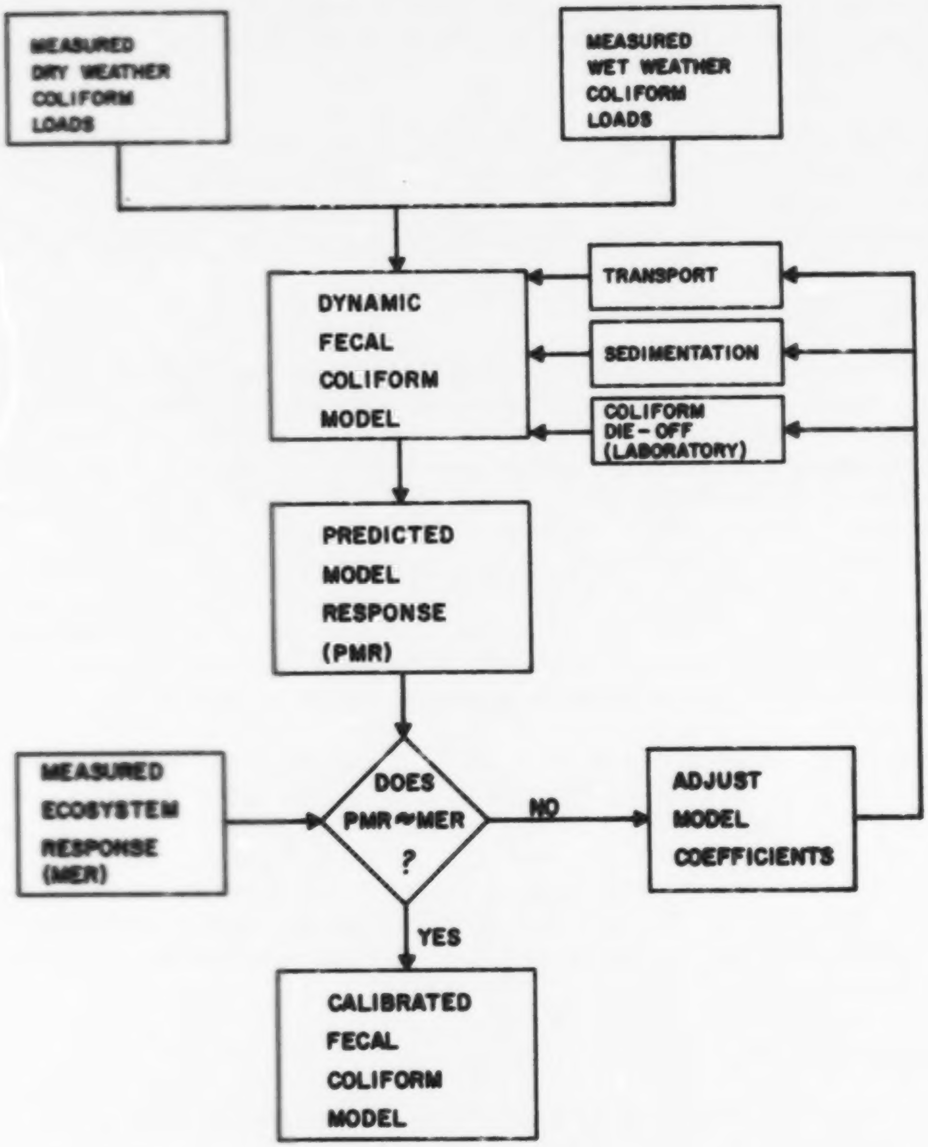

MEASURED DRY WEATHER COLIFORM LOADS
MEASURED WET WEATHER COLIFORM LOADS
DYNAMIC FECAL COLIFORM MODEL
TRANSPORT
SEDIMENTATION
COLIFORM DIE-OFF (LABORATORY)
PREDICTED MODEL RESPONSE (PMR)
MEASURED ECOSYSTEM RESPONSE (MER)
DOES PMR≈MER ?
NO
ADJUST MODEL COEFFICIENTS
YES
CALIBRATED FECAL COLIFORM MODEL

Figure 21. Development of calibrated fecal coliform model.

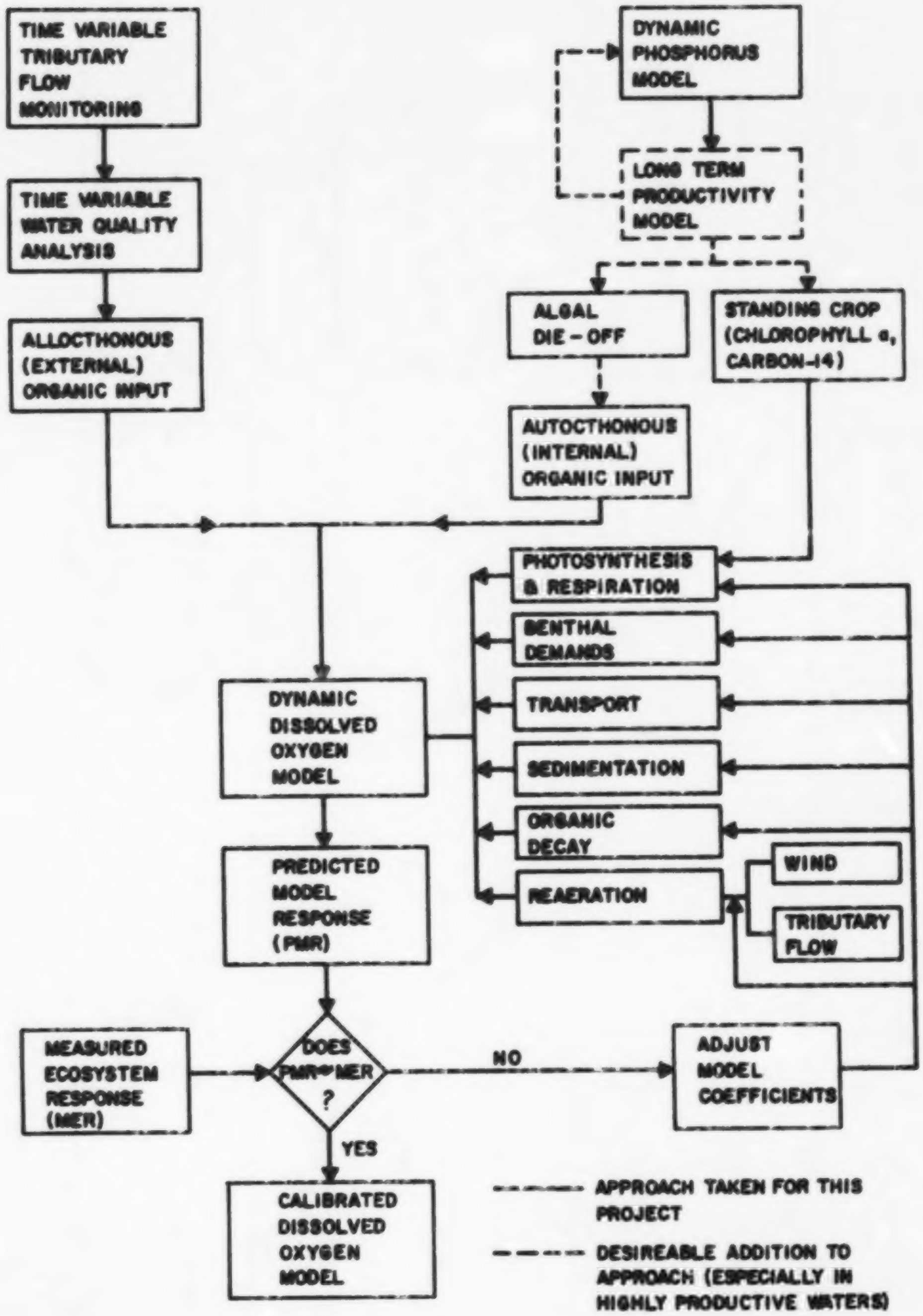

TIME VARIABLE TRIBUTARY FLOW MONITORING
TIME VARIABLE WATER QUALITY ANALYSIS
ALLOCTHONOUS (EXTERNAL) ORGANIC INPUT
DYNAMIC PHOSPHORUS MODEL
LONG TERM PRODUCTIVITY MODEL
ALGAL DIE-OFF
STANDING CROP (CHLOROPHYLL a, CARBON-14)
AUTOCTHONOUS (INTERNAL) ORGANIC INPUT
PHOTOSYNTHESIS & RESPIRATION
BENTHAL DEMANDS
TRANSPORT
SEDIMENTATION
ORGANIC DECAY
REAERATION
WIND
TRIBUTARY FLOW
DYNAMIC DISSOLVED OXYGEN MODEL
PREDICTED MODEL RESPONSE (PMR)
MEASURED ECOSYSTEM RESPONSE (MER)
DOES PMR≈MER ?
NO
YES
ADJUST MODEL COEFFICIENTS
CALIBRATED DISSOLVED OXYGEN MODEL
APPROACH TAKEN FOR THIS PROJECT
DESIREABLE ADDITION TO APPROACH (ESPECIALLY IN HIGHLY PRODUCTIVE WATERS)

Figure 22. Development of calibrated dissolved-oxygen model.

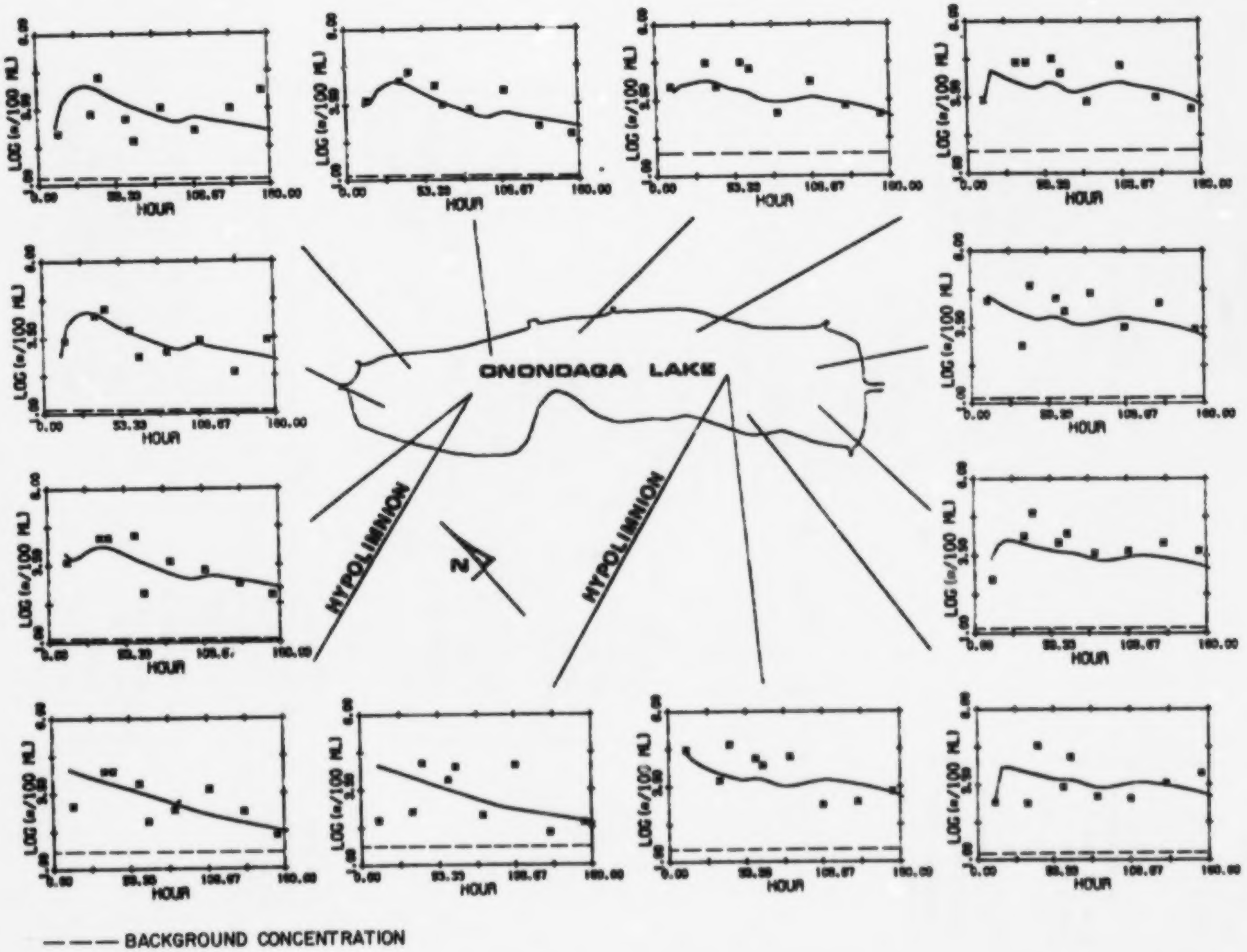


Figure 23. Comparison of measured fecal coliform concentrations with model output. (29).

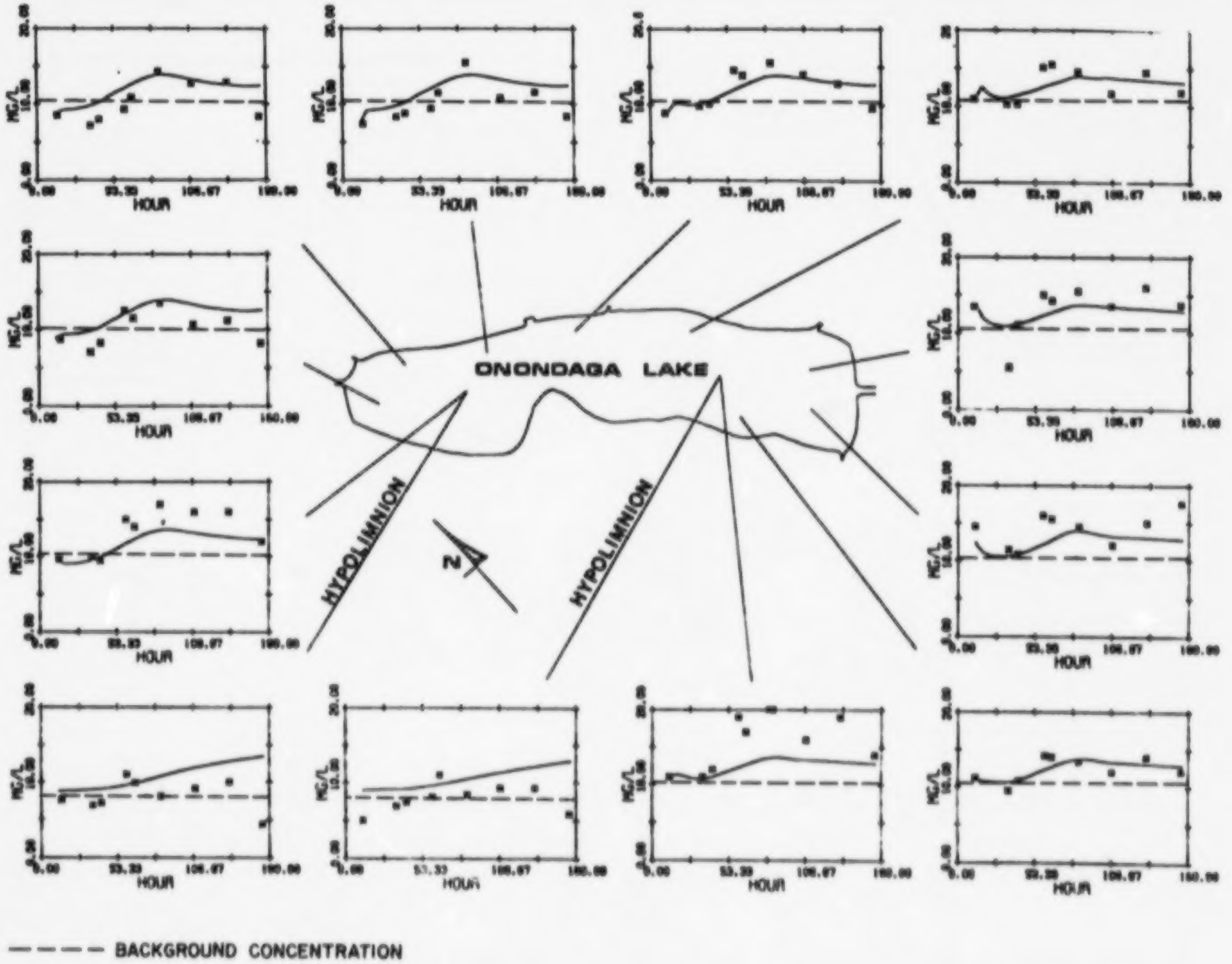


Figure 24. Comparison of measured CBOD concentrations with model output. (29).

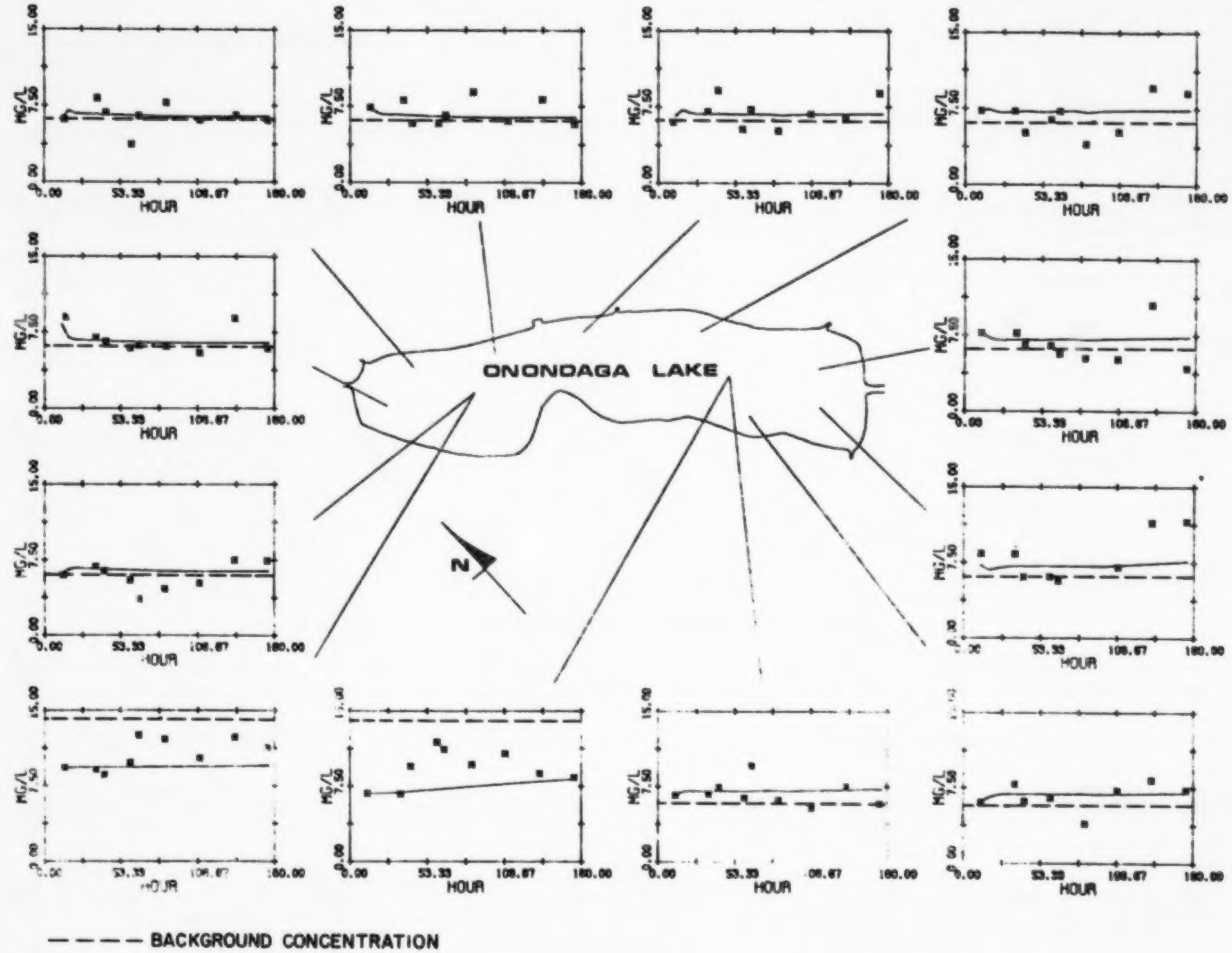


Figure 25. Comparison of measured NBOD concentrations with model output. (29)

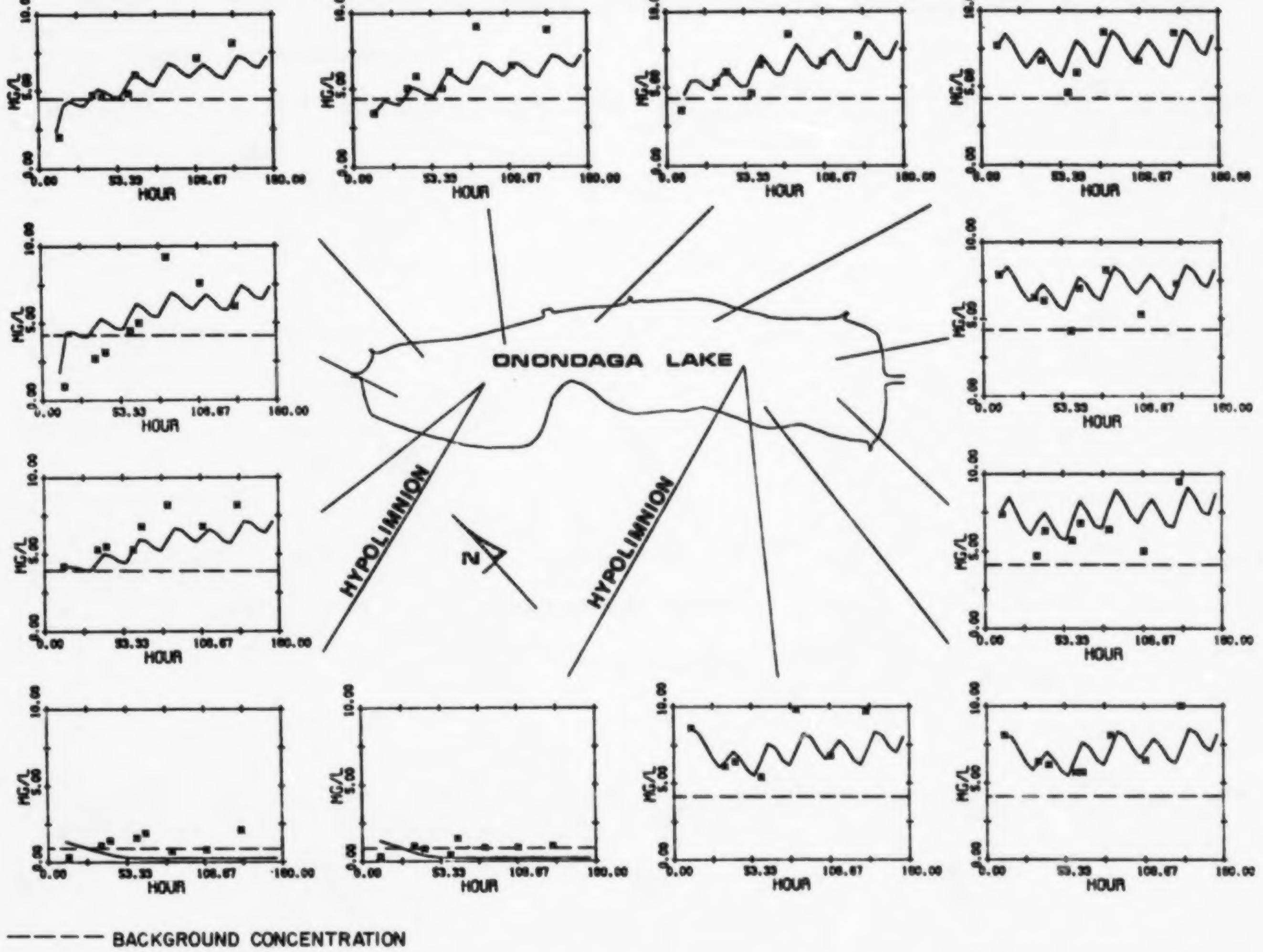


Figure 26. Comparison of measured DO concentrations with model output (29).

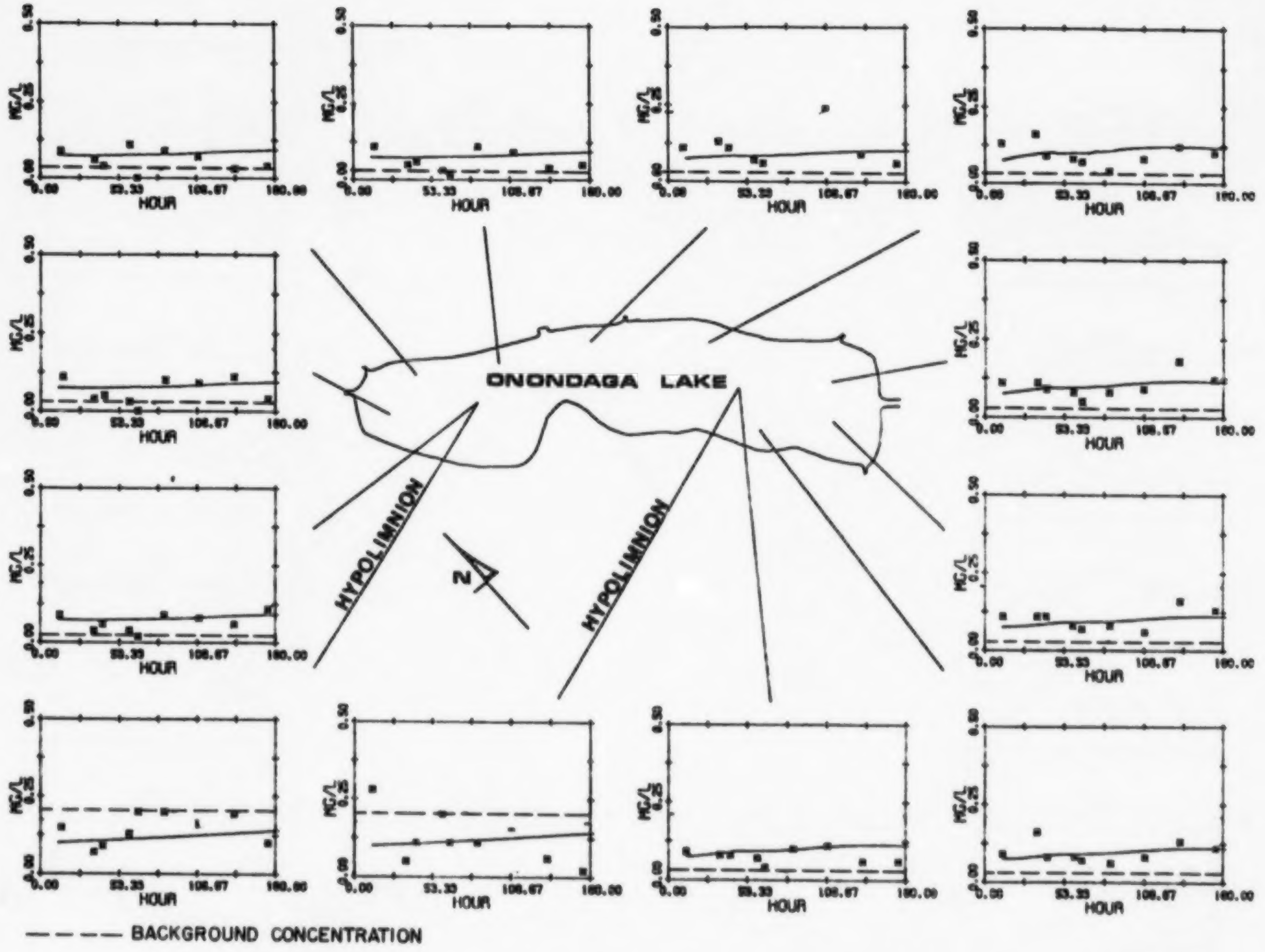


Figure 27. Comparison of measured Total Phosphorus concentration with model output. (29).

minus change in these rates or coefficients should be sufficient to determine the sensitivity of the various parameters.

Tables 11 and 12 are presented as examples of the sensitivity analyses performed on the parameters for Onondaga Lake. These analyses were performed using the steady-state model since this mode of operation saved considerably in computer time while still yielding usable results.

TABLE 11. SENSITIVITY ANALYSIS, REACTION RATES (29)

		Model Results (mg/l)*			
	1975 Monitoring Data (mg/l)*	Calibrated 1975 Model @ $K=K_{model}$	Sensitivity Analysis		
			$K=1.25K_{model}$	$K=0.75K_{model}$	"Bottle" Rates
Fecal Coliform					
Epilimnion	2,100	1,540	1,190	2,100	---
Hypolimnion	180	160	110	250	---
Phosphorus					
Epilimnion	.24	.24	.21	.28	---
Hypolimnion	.54	.55	.56	.56	---
BOD_5					
Epilimnion	4.6	4.7	3.7	6.1	2.5
Hypolimnion	8.3	8.4	7.2	10.5	3.9
TKN					
Epilimnion	2.6	2.5	2.3	2.8	0.4
Hypolimnion	4.6	4.7	4.7	4.7	0.3
Dissolved Oyxgen					
Epilimnion	7.0	8.2	8.0	2.8	3.1
Hypolimnion	2.2	1.2	0.5	2.3	-6.1

*Fecal coliform units = cells/100 ml.

Note: All concentrations apply to south lake basin.
All analyses based on steady state model projections.

TABLE 12. SENSITIVITY ANALYSIS OF PRODUCTIVITY* ON IN-LAKE DISSOLVED OXYGEN

	Dissolved Oxygen (mg/l)	
	Epilimnion	Hypolimnion
Measured (1975 Average Yearly)	7.0	2.2
Calibrated Model (Including Average Yearly Productivity)	8.2	1.2
Net Productivity Increased by 25%	9.7	2.7
Net Productivity Decreased by 25%	6.9	0.0

*Using steady state model (29)

SECTION 9

MODEL PROJECTIONS

The ultimate goal of studies to determine the impact of waste discharges on a receiving water is to predict the waste load that it can assimilate without violation of water quality standards. The impact of a sufficient number of different loads should be determined so that a loading curve such as shown in Figure 28 can be adequately defined. Formulation of the loading curve is generally facilitated by use of the water quality model to project receiving water response to approximately four different levels of pollution. When determining allowable wet weather discharges. the trial levels should include the dry-weather load alone and the dry-weather load plus successively larger wet-weather loads until the receiving water standard is violated. The allowable wet-weather load can then be identified. Since the wet-weather pollutant load is comprised of combined sewer overflows, urban stormwater and non-urban runoff, an estimate of the latter two components is necessary before the degree of treatment required for the combined sewer overflows can be determined.

Figure 29 presents the elements required to develop the loading curve by using the calibrated water quality model. The next two subsections deal with the selection of critical input conditions for the model. including critical transport and environmental conditions, with the projection of both dry-and wet-weather pollutant loads for the model.

CRITICAL INPUT CONDITIONS

Prior to projecting the impact of combined sewer discharges on a receiving water, the critical environmental conditions must be determined for use in the water quality model. These conditions include background water quality, wind speed, incident light, and temperature. Depending on the parameter of concern, the environmental conditions that are critical vary considerably. Table 13 outlines the critical imput conditions required for several models. Even though the same input factors may be critical for two or more water quality parameters, they can act on those parameters in a different manner. For example, fecal coliform impact on water quality is most severe under conditions of low temperature causing minimal die-off and high wind speed resulting in rapid transport to a sensitive

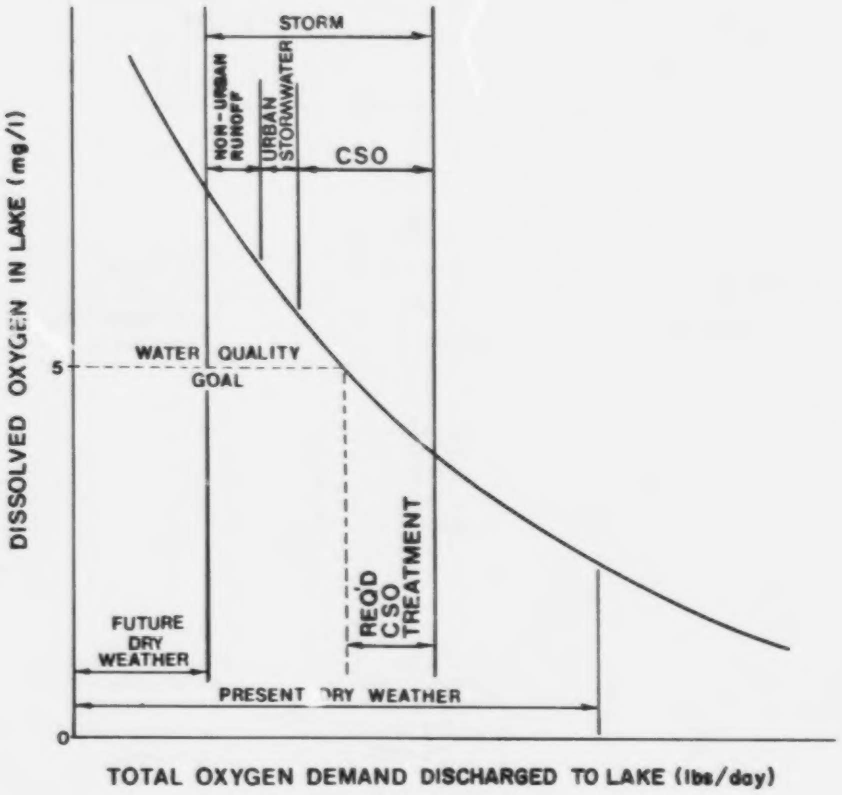


Figure 28. A typical loading curve relating pollutant load to water quality response.

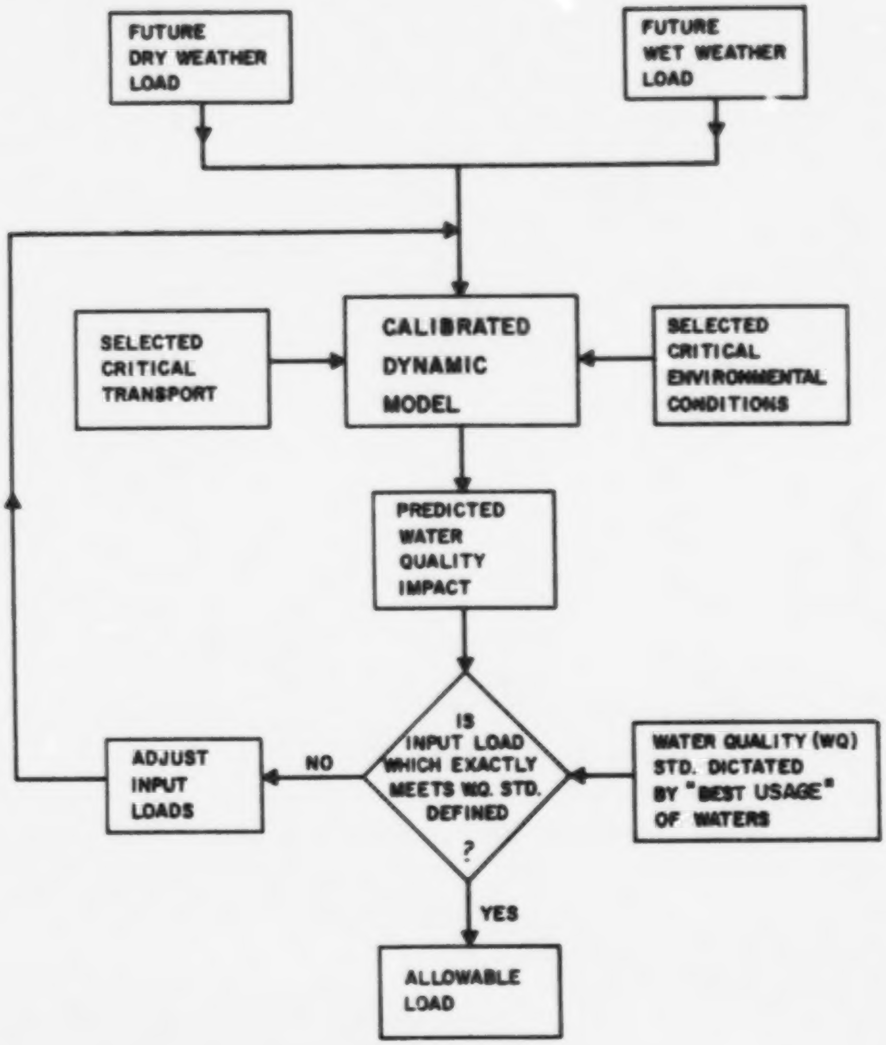

FUTURE DRY WEATHER LOAD
FUTURE WET WEATHER LOAD
SELECTED CRITICAL TRANSPORT
CALIBRATED DYNAMIC MODEL
SELECTED CRITICAL ENVIRONMENTAL CONDITIONS
PREDICTED WATER QUALITY IMPACT
IS INPUT LOAD WHICH EXACTLY MEETS WQ. STD. DEFINED ?
NO
ADJUST INPUT LOADS
WATER QUALITY (WQ) STD. DICTATED BY "BEST USAGE" OF WATERS
YES
ALLOWABLE LOAD

Figure 29. General procedure for developing loading curve and determining allowable load.

TABLE 13. CRITICAL ENVIRONMENTAL CONDITIONS FOR MODEL PROJECTIONS

Critical Input Condition	Type of Water Quality Model Fecal Coliform	 Dissolved Oxygen	 Total Phosphorus
Wind Speed	Yes	Yes	Yes
Temperature	Yes	Yes	No
Light Intensity	No*	Yes	No
Tributary Flow	Yes	Yes	Yes
Tributary Load	Yes	Yes	Yes
Algal Standing Crop	No	Yes	**
Initial Concentration in Each Cell of the Receiving Water	Yes	Yes	Yes

*Included only indirectly since light intensity affects die-off rate.

**Phosphorus and productivity models are interrelated; however, in this case, phosphorus was considered to be conservative and any influence of algal activity is reflected in the net settling rate.

area of the lake, such as a bathing beach; the dissolved oxygen parameter, on the other hand, is most adversely affected by high temperatures when biochemical rates are maximum and at low wind speeds when reaeration is minimal.

Critical water temperature depends on the locale as well as the parameter of concern. Information regarding critical water temperatures can generally be obtained from the state's environmental quality section or from the EPA regional office. It should be remembered that for some parameters, low temperatures are critical, but for others, higher temperatures will have a greater water quality impact. Since most regulatory agencies stipulate a critical temperature for BOD-DO relationships but do not have a critical temperature for bacterial die-off, some monitoring data may be necessary for modeling bacterial parameters.

In predicting the dissolved oxygen content of productive lakes, light conditions and the algal standing crop can have a dramatic effect and can even dominate the DO picture. Historical light data can generally be obtained from the nearest National Weather Service station.

Lake transport is dictated predominantly by wind speed (42). Since historical records are generally not available for lake circulation patterns, the flows to be used in the predictive water quality model must be determined through analysis of wind speed and direction. These data are generally available from the local National Weather Service station or from the NOAA office in Asheville, North Carolina. If the National Climatic Center does not have a station in the community being studied, the national office will provide a list of nearby stations which can provide such data for purposes of approximation.

Onondaga County

Water temperatures used in the predictive model for Onondaga Lake were selected on the basis of eight years of biweekly measurements (43, 44). The contact recreation period was considered to extend from June through September and a realistic low temperature of 20° C (68° F) was chosen. For the dissolved oxygen model, a critical temperature of 25° C (77° F) was selected. Light conditions for the summer months were determined from regional data (45) and corrected by the use of daily percent-cloud-cover measurements from the municipal airport.

Current measurements taken during five storm periods in the summer of 1976 indicated that in-lake circulation patterns (gyres) could be either clockwise or counterclockwise. Based on this information, a circulation pattern was chosen for the predictive runs which provided the most direct transport to the lake shore area of concern. Since the proposed contact recreation area (Figure 6) is located along a northeastern shore, a pattern of counterclockwise gyres in each basin was selected for transport in the bacterial model. Since no one area of the lake is more critical than any other with regard to dissolved oxygen, the gyre selected for the DO model was immaterial. The flow pattern in both cases was directed through the near-shore model cells (Figure 7), with only minor interaction with the mid-lake area. This procedure provided minimum dilution and maintained the wet-weather pollutant slug intact.

The in-lake velocity selected was based on data gathered during the storm monitoring program (46). Ideally, a correlation between wind speed and direction and current movement can be developed, and the critical current velocity can be based on historical wind data. However, despite measurements at ten stations twice daily during each storm, a predictable relationship was not evident. The critical velocities utilized, therefore, were taken directly from the measured data. The values used for the fecal coliform and dissolved oxygen models were the maximum observed of 6.3 mi/day (11.8 cm/sec) and the minimum observed of 1.13 mi/day (2.1 cm/sec), respectively.

For the predictive bacterial model runs, the dispersion coefficients were decreased so that the peak of the bacterial slug was minimally reduced by dispersion. Thus, reduction of peak coliform concentrations in the predictive model runs were primarily the result of die-off. These transport conditions produced maximum coliform impact in the epilimnion of the contact recreation zone.

Wind speed is an integral part of the dissolved oxygen model since it is the primary driving force of reaeration. The average monthly minimum seven-consecutive-day wind speed was used in the dissolved oxygen model. It was used instead of a more severe condition because the probability of occurrence of a low frequency storm (e.g., one-year, two-hour storm) coincidentally with this wind velocity was more realistic. For Onondaga Lake, the value of 3.9 mph (6.4 km/hr) was determined from analysis of six years of summer wind data.

PROJECTED POLLUTANT LOAD

The total projected pollutant load for storm-related water-quality studies consists of a dry- and a wet-weather component. The dry-weather component, comprised of both point and non-point sources, can generally be expressed as a continuous steady-state function. The wet-weather component is generally dynamic; however, it may be represented satisfactorily in certain cases as a series of step functions. Representing the total load in this approximate manner can save considerably in computer time and may permit a simplified sewer system model to be used to estimate the load.

The dry-weather component of the load is comprised of municipal and industrial discharges and the contribution of tributaries that is not directly associated with rainfall-runoff. The quantity and quality of discharges from municipal and industrial wastewater treatment facilities can be determined from information:

1. Stored in the data storage and retrieval system of the EPA (STORET);
2. Submitted by the discharger as part of the self-monitoring program of the National (or State) Pollutant Discharge Elimination System (NPDES or SPDES);
3. Collected during independent monitoring programs conducted by regulatory or other governmental agencies or by educational institutions;
4. Published by local or state planning agencies concerned with the area's growth over the design period.

The quantity of pollutants discharged to a lake by tributaries can be determined from:

1. STORET data;
2. Monitoring programs conducted under Section 303e of PL 92-500, which are available from the state's water quality section or EPA;
3. Independent monitoring programs.

Sources 1 and 3 above could potentially provide enough long-term historical data to determine a dry-weather load statistically. The 303e Studies generally do not provide long-term data but can provide usable quantity and quality information under dry-weather conditions. Flow records for gaged tributaries can be obtained from the local office of the United States Geological Survey (USGS), the U. S. Army Corps of Engineers, or the state's department of environmental protection. If quantity and quality information is not available for a particular tributary, records from a similar stream may be used if corrections are made for drainage area and land use.

The wet-weather component of the pollutant load is comprised of contributions from upland and non-urban runoff, urban stormwater, and discharges from combined sewer overflows. The quantification of each of these pollutant sources is required if the degree of treatment required for the CSO system is to be determined; however, complete projection of wet-weather loads for these sources requires costly predictive modeling of each component. Such modeling may be unnecessary and wasteful, depending on both the relative magnitude of the discharges and whether the pollutographs of the various elements superimpose on each other (7). These two factors are related to the size of the drainage areas, location of the urban center within the drainage area, and overall response time of the various sources.

A pragmatic approach for determining the significance of the various wet-weather components is to first evaluate the relative magnitudes of the sources through an expanded monitoring program conducted simultaneously with the monitoring of the CSO system. The sampling program requires that quantity and quality measurements be made on all tributaries above and below the urban area. The upstream sample identifies the upland runoff; the difference between it and the downstream sample quantifies the urban component. To distinguish between the CSO and stormwater portions of the urban component, the load from the CSO system must be determined. For each storm monitored, the data from the monitored areas can be applied to the unmonitored areas so as to project an overall CSO load. Using this method, the contributions of the various wet-weather sources can be compared for relative impact.

If the contributions from either the urban stormwater or rural runoff prove to be significant for a given parameter, projection of this component for the design storm condition will be necessary. Since mathematical modeling of these components is generally beyond the scope of CSO studies, estimates must be made on the basis of measured data. The estimates are generally based on data collected during the CSO study, since wet-weather information is rarely available from other sources. Any historical data is generally skewed toward dry-weather information. As a first trial, the most severe upland load actually measured should be used and superimposed on the projected CSO load.

Onondaga County

Onondaga Lake is unique in that the County of Onondaga has conducted a yearly monitoring program (43, 44) in addition to conducting a comprehensive baseline study (41). The data collected during these two programs made possible the selection of truly representative dry-weather tributary waste loads. The number of years of record used in determining these background loads depends on when and if major changes within the particular drainage basin have occurred. Examples of such changes in Onondaga County were abandonment of a landfill site, adoption of a more effective sewer maintenance program, modification of treatment facilities, and the state-wide banning of detergents containing phosphorus. Depending on the tributary, anywhere from two to six years of biweekly data were analyzed to arrive at the average-summer dry-weather influent load. The discharge load selected for the Metropolitan Wastewater Treatment Facility corresponded to the design efficiency of the plant now under construction.

Table 14 presents the dry-weather discharges received by Onondaga Lake. Since the times of concentration for the drainage basins tributary to Onondaga Lake far exceeded the response time of the CSO system, the upland non-point component was ignored and pollutant loads generated during storms were taken as the sum of the dry-weather and CSO loads. Since only a small percentage of the urban area has separate storm and sanitary sewers, urban stormwater was also ignored.

Table 15 presents the wet-weather pollutant loads for the one-, two- and ten-year storms; they were superimposed on the dry-weather loads presented in Table 14.

LAKE MODEL PROJECTIONS

The useful end-products of water quality models, including lake models, are primarily their cause-and-effect projections relating improvements in receiving water quality to proposed or contemplated changes in pollutant loads. The remainder of this section will be devoted to examining the products of the Onondaga Lake modeling as examples of such projections.

Results - Onondaga Lake

In-lake fecal coliform concentrations were projected using the calibrated model for one dry-weather loading condition and three wet-weather loads which bracketed contravention of the bacterial standard of 200 cells/100ml. Table 16 shows the impact of the one-year (two-hour) storm on the bacteriological quality in the contact recreation zone. Also shown is the time of recovery (TOR), i.e., the time required for the quality to return to an acceptable level. Dissolved oxygen deficit projections, also shown in Table 16, will be discussed in later paragraphs.

Figure 30 shows the fecal coliform loading curve generated for the lake. As may be seen from the figure and Table 16, the dry weather discharges alone produce a peak fecal coliform concentration of 120 cells per 100ml in the recreation zone of the lake. However, the dry-weather effect should not be as severe once the upstream pollutant sources of Onondaga Creek are eliminated. This figure demonstrates the dramatic effect that CSO's have on the bacteriological quality of Onondaga Lake. The one-year, two-hour storm causes the fecal coliform concentration to exceed 10^4 cells/100ml in the contact recreation zone and remain in violation of the

TABLE 14. DRY-WEATHER POLLUTANT LOADS

Tributary	Flow (mgd)	Influent Load (lbs/day)					
		Carbonaceous BOD	Ammonia Nitrogen	Organic Nitrogen	Dissolved Oxygen	Total Inorganic Phosphorus(1)	Fecal Coliform(2)
MSTP(3)	80.0	5,000.	--	6,670.	1,335.	665.	0.60
Onondaga Creek	100.0	5,170.	590.	785.	2,000.	248.	65.20
Ley Creek	28.0	1,775.	320.	110.	1,070.	183.	1.81
Harbor Brook	10.0	1,510.	145.	110.	250.	88.	29.20
NineMile Creek	123.0	4,190.	820.	550.	1,760.	131.	0.
Allied Chemical East Flume	56.0	735.	1,350.	500.	1,600.	7.	0.54
Crucible Steel	0.4	65.	10.	5.	40.	4.	0.006
TOTALS	397.4	18,445.	3,235.	8,730.	8,055.	1,326.	97.36

(1) Average daily loading rate based on yearly monitoring data; not dry-weather loads.
(2) Units = (10^{12} cells/day)
(3) Loads based on tertiary treatment at Metropolitan Sewage Treatment Plant.
(4) 1 kg = 2.2 lbs.

TABLE 15. WET-WEATHER POLLUTANT LOADS[1]

Tributary	Flow (mgd)	Influent Load (lbs/day)				
		Carbonaceous BOD	Ammonia Nitrogen	Organic Nitrogen	Total Inorganic[2] Phosphorus	Fecal Coliform[3]
ONE-YEAR, TWO-HOUR STORM						
Onondaga Creek	182.4	138,200.	3,790.	2,110.	480.	13.0
Ley Creek	48.0	16,600.	120.	310.	58.	7.2
Harbor Brook	28.8	19,400.	130.	365.	48.	
TWO-YEAR, TWO-HOUR STORM						
Onondaga Creek	330.7	250,700.	6,850.	3,795.	870.	(4)
Ley Creek	72.5	24,900.	180.	470.	87.	(4)
Harbor Brook	50.2	34,000.	225.	635.	87.	(4)
TEN-YEAR, TWO-HOUR STORM						
Onondaga Creek	548.6	415,500.	11,355.	6,308.	1,426.	(4)
Ley Creek	154.3	53,200.	387.	1,011.	185.	(4)
Harbor Brook	68.6	46,300.	113.	864.	113.	(4)

(1) Wet-weather pollutant loads and flow for the 1-, 2- and 10-year storms were applied at these rates over 5, 5.5 and 7 hours, respectively.

(2) Due to the long-term effect of phosphorus loads, average daily wet-weather loads were entered into the steady-state model.

(3) Units = 10^{15} cells/day.

(4) The impact of these loads was not modeled since dramatic effects were noted at a much lower loading level.

200 cells/100ml standard for nearly 3.3 days. To meet the water quality standards, greater than a two-order magnitude of reduction in the fecal coliform discharge from the CSO system is required.

TABLE 16. PROJECTED IMPACT OF WET-WEATHER LOADS ON ONONDAGA LAKE

		Storm Recurrence Interval		
	Pre-Storm	1 Year	2 Years	10 Years
FC (cells/100ml)*	120	10^4	**	**
TOR (days)	-	3.3	**	**
DO Deficit (mg/l)	0	0.39	0.48	0.90
TOR (days)	-	Negl.	2.97	4.37

---

*Occurring in epilimnion of contact recreation zone.

**Not modeled since dramatic effects were noted with much more frequent storms. Two additional model runs were performed for storms occurring more frequently than once per year to define the loading curve (Figure 30).

Onondaga Lake historically has had dissolved oxygen deficiency problems (4) which were attributed to the large waste loads that the lake receives. During this study it became evident that the dissolved oxygen picture of the lake was controlled predominantly by fluctuations in the algal biomass. Dramatic die-off of the algal standing crop occurs quite frequently in Onondaga Lake and the dead cells contribute substantially to the carbonaceous BOD of the lake. A die-off of biomass equivalent to 86 μg/l chlorophyll a (the estimated peak concentration after tertiary treatment is implemented (47)) over a two-week period produces an average decrease of 9 mg/l in dissolved oxygen. Biomass fluctuations of this magnitude are not uncommon and, in fact, during the monitoring program for the Storms Impact Study (46), a die-off of 130 μg/l of chlorophyll a was observed during a similar period.

The DO deficit resulting from wet-weather discharges is negligible when compared to the deficits resulting from algal die-off. Table 16 shows the deficits produced by the one-, two- and ten-year storms together with the time needed to return to within 5 percent of the initial condition (TOR). The minimum dissolved oxygen concentration produced by the ten-year storm load is 6.9 mg/l under the selected environmental conditions. Based

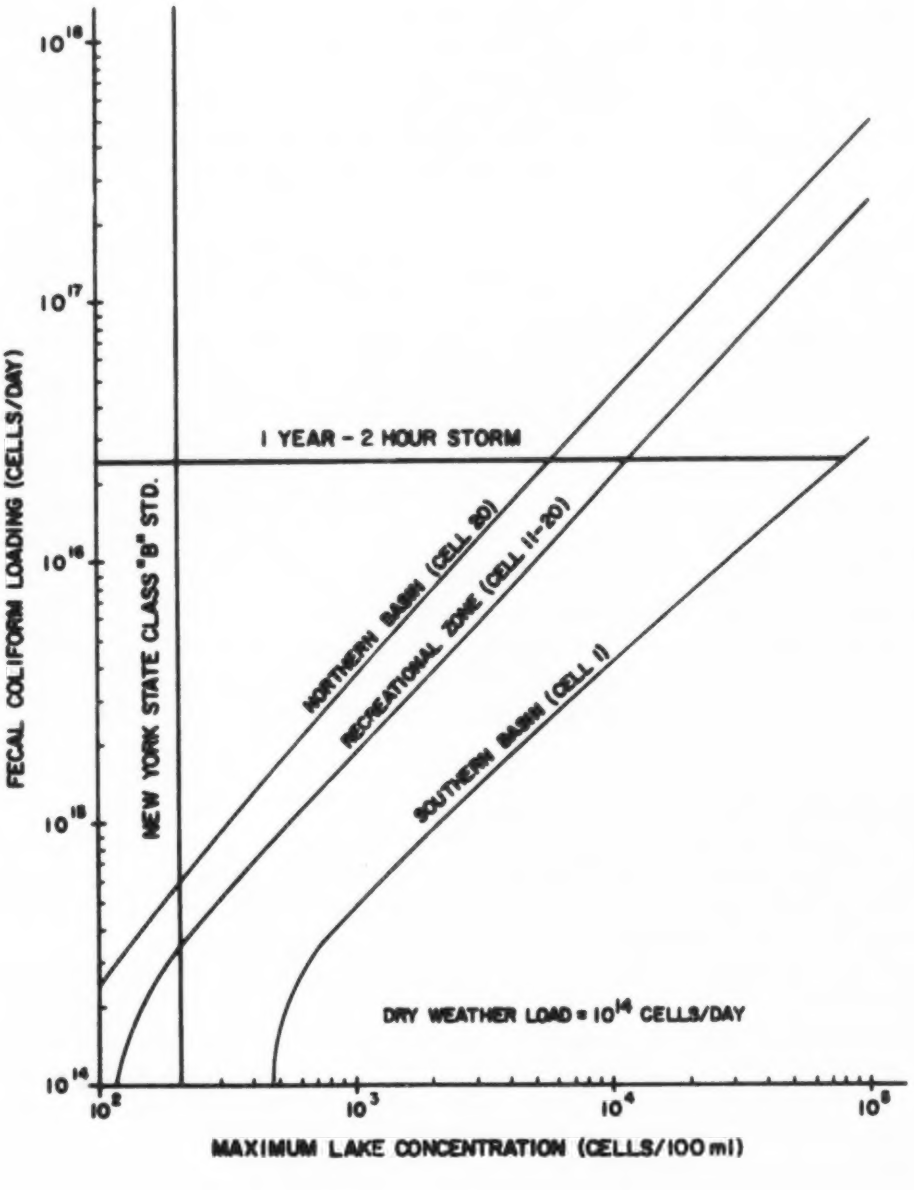


Figure 30. Fecal coliform loading curves for Onondaga Lake.

on this information, the final abatement plan does not consider removal of organics as a primary goal.

Due to the long-term effects of nutrients, the impact of phosphorus contributed from the CSO's was evaluated with the steady-state model. The calibrated phosphorus model was run at the following two input conditions:

1. Average daily total inorganic phosphorus load (Table 14), based on monitoring data, including projected phosphorus reductions at the Metropolitan Sewage Treatment Plant.

2. Condition 1 above, plus the average daily CSO phosphorus load; the average daily CSO load is approximately 13 lbs/day (28 kg/day) (6).

Table 17 compares the results of the runs and shows that the phosphorus contributed from the combined sewer system produces only a 1 percent change in concentration in the lake.

TABLE 17. AVERAGE ANNUAL PHOSPHORUS CONCENTRATIONS IN ONONDAGA LAKE

Loading Condition	South Basin (mg/l)		North Basin (mg/l)	
	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion
Average Daily: Without CSO Component	0.221	0.508	0.204	0.495
Average Daily: With CSO Component	0.223	0.513	0.206	0.500

The wet-weather load produces such a minute change within the lake, compared to other sources, that wet-weather treatment for phosphorus removal was not considered in the abatement plan.

SECTION 10

COST-EFFECTIVENESS ANALYSIS

The development of relationships between rainfall, overflow discharges, and their receiving water impact is the essential basis for a cost-effective abatement program. In the case of conventional dry-weather treatment, receiving water quality is focused on established state standards and prescribed low flow conditions. Such pre-set conditions do not exist with respect to stormwater treatment because of the variable nature of stormwater runoff and the premise that not all of the runoff can be economically captured and subsequently treated. The approach in stormwater treatment has been to develop relationships between receiving water impact and the cost of treatment for various storm conditions so that local governments and regulatory agencies can be provided with the cost-benefit information needed to make reasonable decisions. This section will summarize the relationships unique to the CSO problem and will present a method for selecting an optimum treatment level.

CSO RELATIONSHIPS

Rainfall Patterns

To determine the extent to which a particular area is subject to stormwater pollution, the most fundamental information that must be analyzed is the seasonal and annual rainfall. As discussed in Section 7, a number of statistical routines are available to analyze long-term rainfall data. Rainfall can be classified according to monthly totals so that a typical pattern can be developed and so that critical months can be determined, as shown in Figure 31. Similar plots can be made depicting average rainfall, intensity, duration, antecedent dry weather, or number of storms in the respective months. These data, in conjunction with receiving water flows, can be used to select the months or periods in which the most significant pollution may occur. The simple planning models described in Section 7, such as SSWMM and STORM, can be utilized to make gross estimates of the number and quantity of overflows that occur over periods of days or years.

Given a long-term record of rainfall, the classic system of curves relating rainfall intensity to duration can be developed for various storm

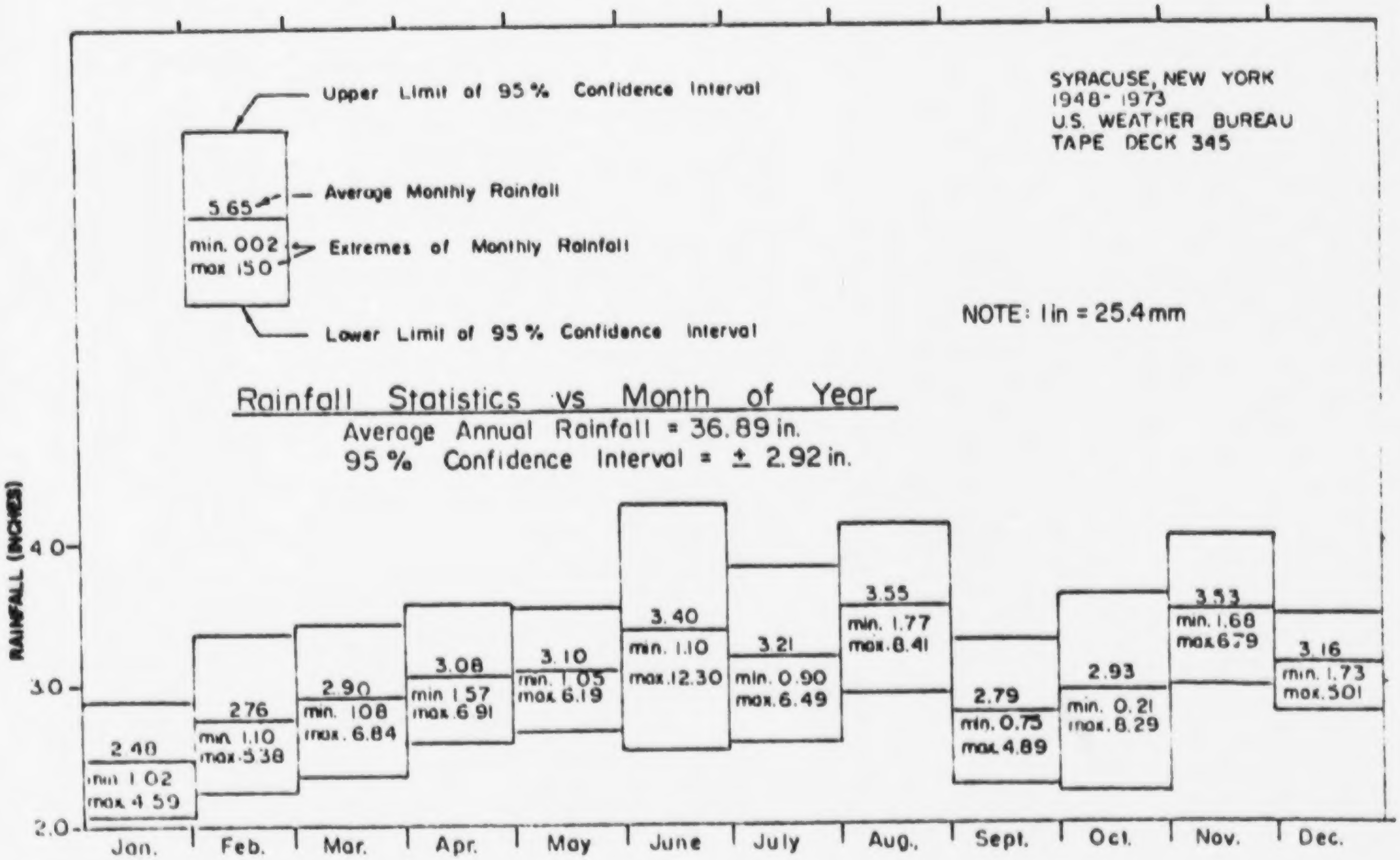


Figure 31. Summary of monthly rainfall data (6).

frequencies or return intervals, as shown in Figure 32. Such curves are used to classify storms in relation to pollution and to treatment costs, as outlined later in this section.

Receiving Water Impact

In order to link pollutant quantities to their water-quality impact, a relationship must be developed which accommodates dry-weather sources as well as stormwater sources. Dry-weather inputs should reflect current treatment requirements for both publicly owned and industrial treatment works; if such facilities are not presently in operation, future dry-weather inputs should be projected and included. Stormwater inputs should include upstream non-point sources, urban stormwater in areas separately sewered, and combined sewer overflows. Since this last component represents the greatest potential health hazard and is generally the most controllable entity, it is the component for which cost-effective analyses will be described herein. It is recognized that at some point in the treatment of CSO's, urban stormwater, non-point source pollutants, or additional dry-weather inputs may be more cost effective to remove than the CSO's.

Figure 28 illustrates the foregoing pollutant sources as they might relate to the dissolved oxygen requirement in a lake. Providing that the receiving water can sustain all but a portion of the CSO sources, the pollutant quantity requiring treatment can then be varied for different storm conditions. While a pollutant quantity might represent a specific water-quality goal, it is likely that regulatory agencies and the public would be interested in the abatement costs associated with varying degrees of contravention and compliance; thus, a range of treatment bracketing the identified storm should be depicted. These relationships are explained in greater detail further in this section.

CSO Discharges

The quantity of pollutants discharged by a combined system is dependent on several factors. It can be expected that storms of greater intensity will result in greater flows through the system and will generate higher velocities which will enhance the scour of pollutants accumulated either on the land surfaces or along pipe inverts. The duration over which an intensity of rainfall occurs will determine the quantity of available pollutants that are scoured from the system. The extent of pollutant accumulation prior to a storm occurrence will depend on: (a) the residual of pollutants remaining at the end of the previous storm; and (b) the amount accumulated during the intervening period, commonly referred to as the Antecedent Dry Weather Period (ADW).

Quantities of pollutants discharged under a particular set of storm

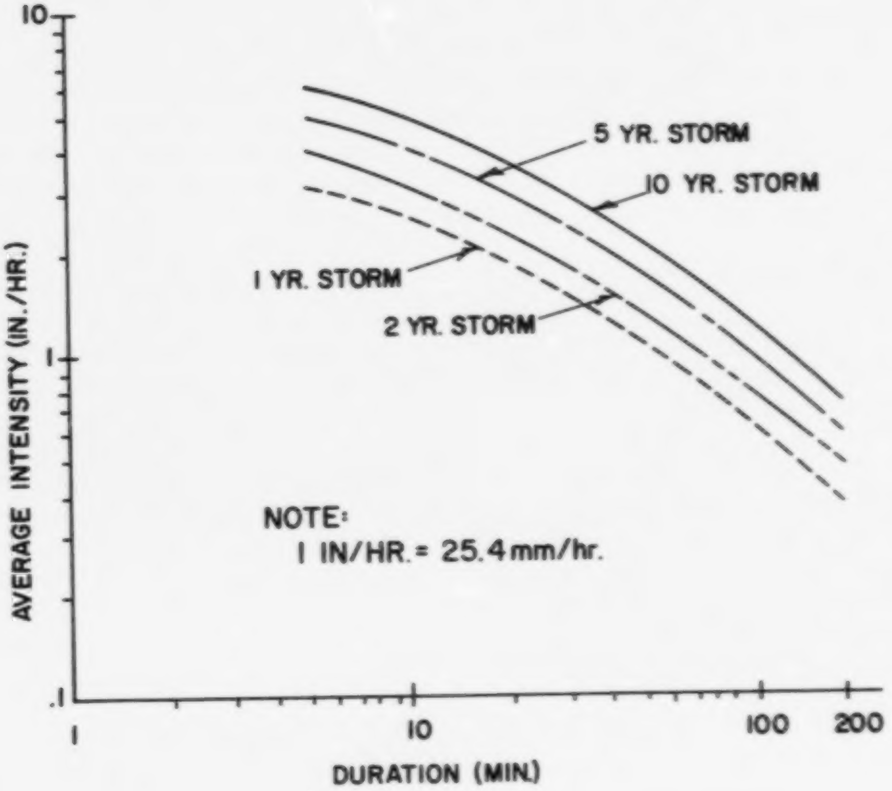


Figure 32. Intensity - duration- frequency curves, Syracuse, New York.

conditions can be calculated through the use of the SWMM, or statistically derived relationships, or a combination of both. Generally, SWMM can be employed to develop flow quantities or hydrographs, whereas SWMM or statistically derived relationships can be used to arrive at qualitative yardsticks, such as the pollutographs and loadographs previously described and illustrated.

If the residual pollutants and the ADW are kept constant, pollutant load discharged can be related to various types of storms in terms of recurrence interval. Appropriate residual pollutant and ADW quantities can be derived from statistical analyses of data or from the literature. The deposition is dealt with in greater detail elsewhere (48, 50).

ABATEMENT COSTS

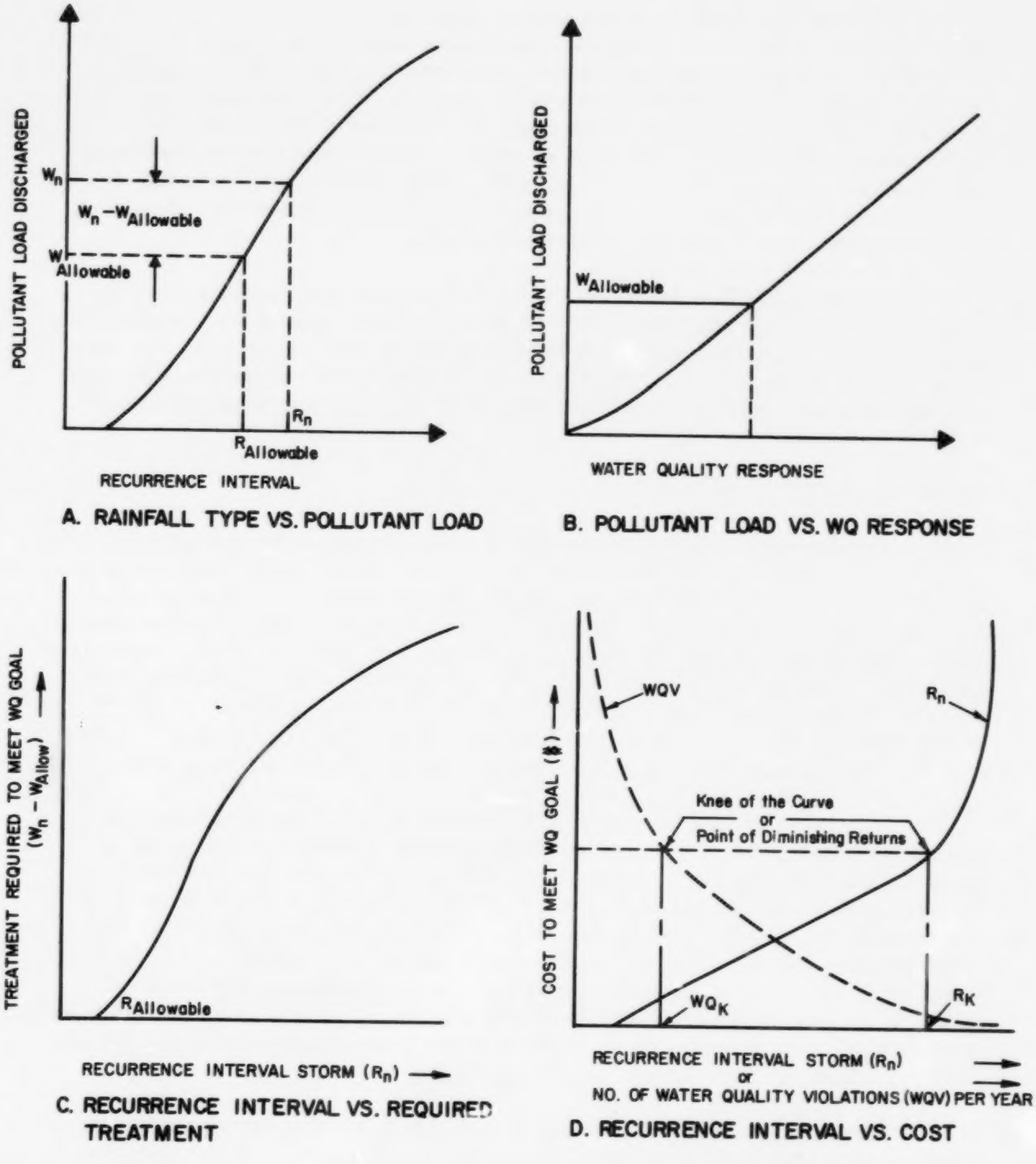
Figure 33 illustrates the interrelationships between the various phases of a CSO study and shows the development of a cost-effective treatment solution.

Figure 33A illustrates the relationship between the pollutant loads discharged from a CSO system and various storm conditions described in terms of recurrence interval. Recurrence interval can be used in this manner only if other significant factors such as pollutant residual and ADW are held constant. Recurrence interval is an appropriate variable from the standpoint of the general availability of data and relationship to abatement costs.

Generally several years of rainfall records are available whereby frequency of overflow can be determined on the basis of sewer system capacity. Such information, in combination with even limited quality information, can be used to determine the pollutants discharged from a system over a period of years. This is accomplished either through a series of single-event calculations or continuous simulation, as described in Section 7.

The significant factors in developing costs of abatement strategies are flow rate and volume, which are derived from the characteristics of recurrence interval, namely, rainfall intensity and duration.

Figure 33B illustrates the relationship between pollutant load discharged from the sewer system and water quality response. This relationship is developed and discussed in Section 8. Based on a selected water-quality goal, the allowable pollutant load determined from Figure 33B can be related to an allowable recurrence interval from 33A. Although the relationships illustrated by Figures 33A and 33B can represent independent study efforts, they can be interfaced through the development of the common relationship to pollutant load.



A. RAINFALL TYPE VS. POLLUTANT LOAD

B. POLLUTANT LOAD VS. WQ RESPONSE

C. RECURRENCE INTERVAL VS. REQUIRED TREATMENT

D. RECURRENCE INTERVAL VS. COST

Figure 33. Procedure for establishing the most cost-effective treatment level to meet a given water quality goal.

Figure 33C illustrates the relationship between treatment required and recurrence interval. This relationship is based on a series of points selected from Figure 33B, and can be expressed in terms of the pollutant load in excess of the allowable (W_n-$W_{allowable}$). The treatment requirements set the basis upon which the cost of a treatment facilities can be determined. The various methods of source control and the various treatment options are reported elsewhere (17). The specific unit processes available and the associated unit costs for both construction and operation and maintenance are well documented (18, 49).

Figure 33D illustrates the cost of treatment as it relates to both recurrence interval and the number of water-quality violations. It should be noted that the costs represent the least expensive mix of control and treatment options in each case. These costs are developed on the basis of engineering judgment and relationships developed through previous studies (50, 51).

COST-EFFECTIVE SOLUTION

Treatment costs can be related directly to either recurrence interval or a measureable benefit, which in this case has been illustrated as the number of water-quality violations per year. Since recurrence interval (R_n) serves as the basis for determining the frequency of overflow in the system, the number of water-quality violations can be directly equated to recurrence interval. Another method to determine the number of water-quality violations is through the use of continuous simulation, whereby the number of violations per year for a particular treatment scheme are calculated. Costs can then be plotted against the average annual benefit as shown in Figure 33D.

For the example selected, the knee of both curves shown occurs at the same cross point. The "knee" of the curves represents the point of diminishing returns. Below the knee, treatment may be as cost effective but will result in less removal and subsequently more frequent violations of the water-quality goal. At all points beyond the knee, the additional benefits derived from incremental increases in expenditure decrease rapidly and are commonly referred to as being beyond the point of diminishing returns. While it may be desirable to meet water-quality standards beyond the "knee", justification should be based on factors other than economics (e. g. , legislative decisions or "best usage" of the receiving water).

A more comprehensive method of presenting abatement costs and associated benefits involves performing the above procedure for various water-quality goals (see Figure 33B). Figure 34 shows a plot of costs versus water-quality violations for various goals in order to illustrate the economic impact of more or less stringent goals. Such an approach can be used to determine the most cost-effective water-quality goal or "general

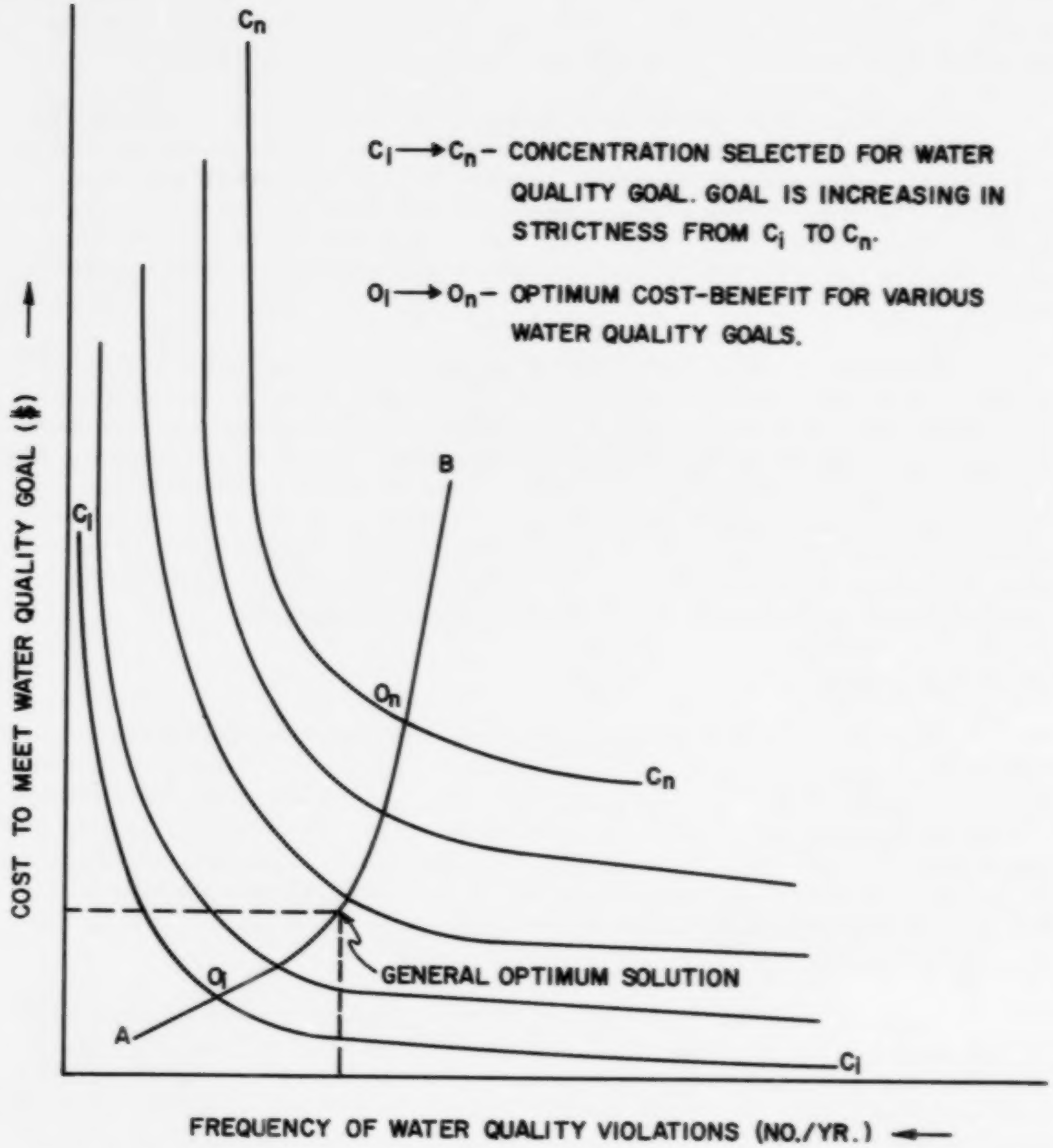

C_n
$C_l \longrightarrow C_n$ - CONCENTRATION SELECTED FOR WATER QUALITY GOAL. GOAL IS INCREASING IN STRICTNESS FROM C_i TO C_n.
$O_l \longrightarrow O_n$ - OPTIMUM COST-BENEFIT FOR VARIOUS WATER QUALITY GOALS.
COST TO MEET WATER QUALITY GOAL ($) →
B
C_l
O_n
C_n
GENERAL OPTIMUM SOLUTION
O_l
A
C_l
FREQUENCY OF WATER QUALITY VIOLATIONS (NO./YR.) ←

Figure 34. Procedure for determining the cost effective water quality goal.

optimum solution" (GOS). The term GOS is used herein to denote a solution which encompasses the essential factors necessary to arrive at a reasonable solution. Figure 34 presents a summary of these factors from which the decision-makers can select a reasonable water-quality objective.

The GOS can be determined by drawing a curve (A-B in Figure 34) through the knees of a series of cost curves similar to the one presented in Figure 33D. The general optimum solution to the cost-benefit analysis occurs at the knee of this curve. This point not only defines the water-quality standard and associated cost, but through the use of Figure 33D, indicates the probable frequency with which that standard will be contravened.

It should be noted that in some cases data will not yield a noticeable break or knee at which the GOS occurs. However, in any event, presentation of the data as shown in Figure 34 will be desirable since it provides the complete picture of the water-quality benefits which can be expected for any given expenditure. Even though a GOS exists, it may be desirable for a variety of reasons (e. g. , limited funds or inability to live with the cost-effective water-quality goal) to select another water-quality goal. The cost data presented in Figure 34 enables the decision-makers to balance the water-quality goals against the total cost of achieving them.

Onondaga County

As discussed in Sections 7 and 9, curves relating various recurrence-interval storms, CSO discharges and water quality were developed for the Onondaga Lake study. In that case, the analyses showed fecal coliform to be the only parameter to show significant water-quality impact from the CSO discharges. Therefore, only examples of abatement solutions related to meeting the contact recreation standard of 200 cells/100 ml established by the New York State Department of Environmental Conservation will be discussed in this section.

Extensive statistical analyses of rainfall patterns were performed on the historical records for Syracuse, New York, and the results compared to the findings of both the CSO and the water-quality programs. This procedure revealed that there are 170 rainfall events per year; based on peak intensity, 65 of these produce overflows. On the average, the combined sewer system is capable of accepting the runoff from a storm with peak intensity of less than 0. 05 inches/hour without causing any overflow. Of these 65 overflow-producing events, only 38 result in discharges of sufficient magnitude to cause a violation of the fecal coliform standard in the contact recreation zone. Figure 35 presents the number of violations that occur annually as a result of treating storms of various intensities or recurrence intervals for a fixed two-hour duration. Figure 36 shows the

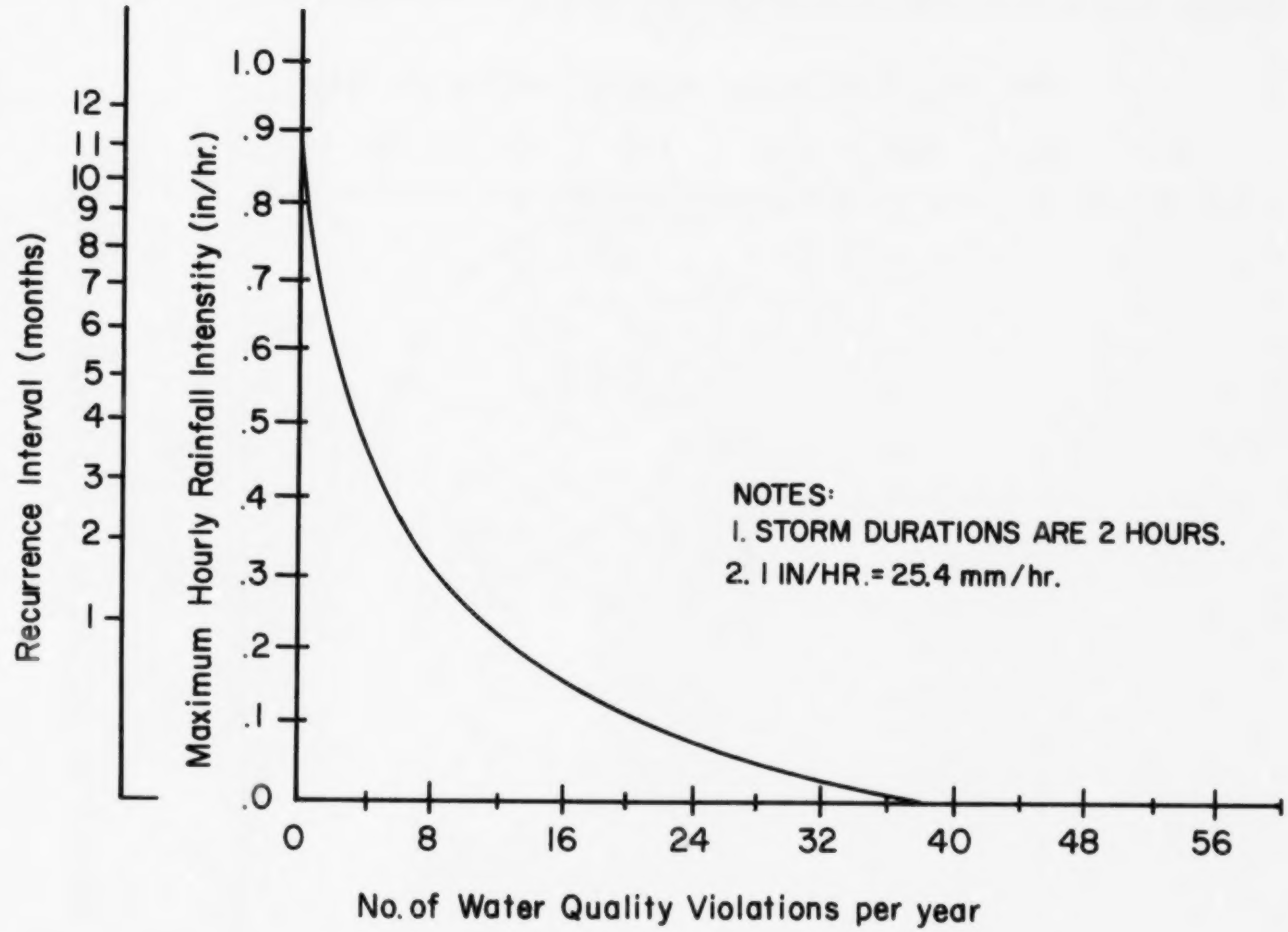


Figure 35. Number of water quality violations occurring annually in Onondaga Lake as a result of treating various intensity storms (6)

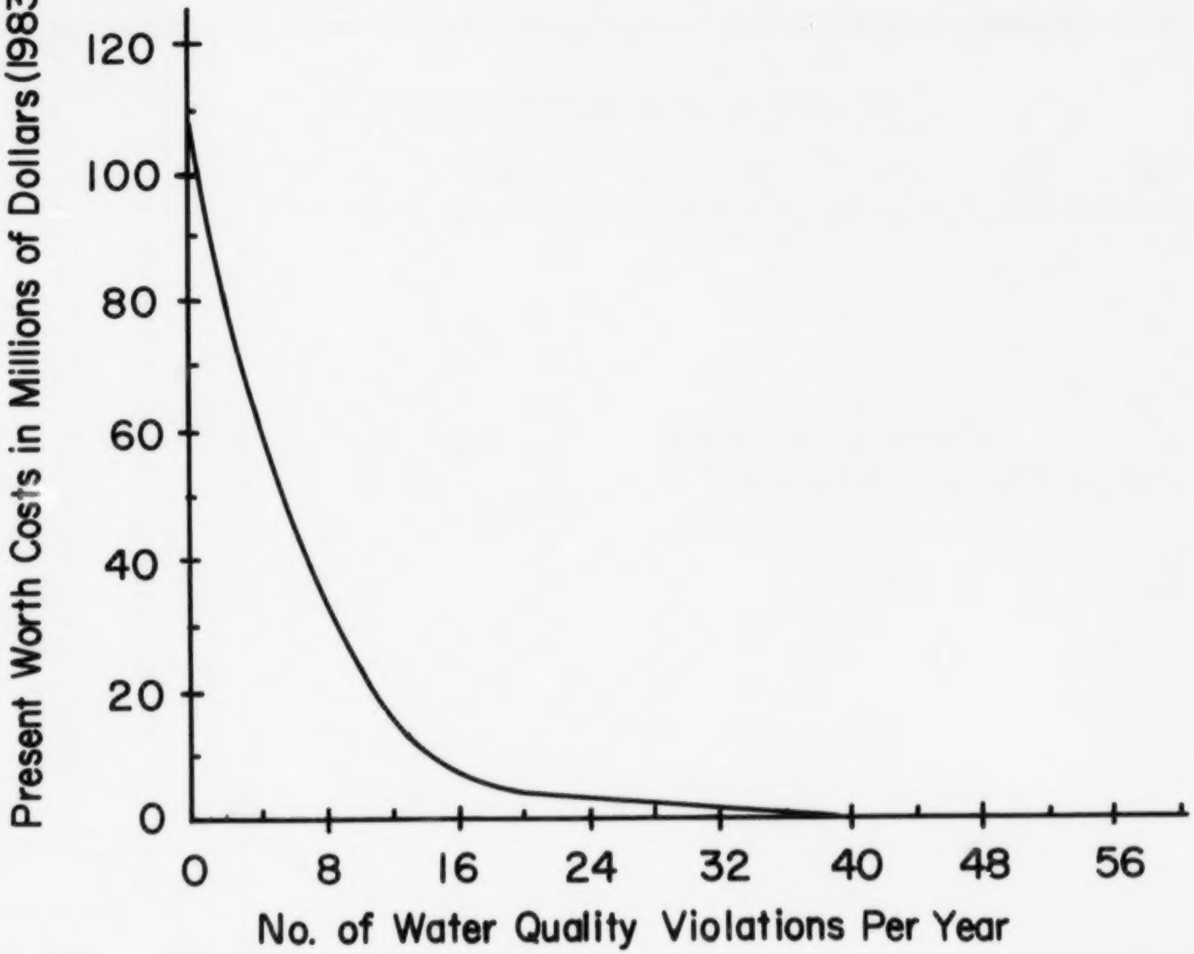
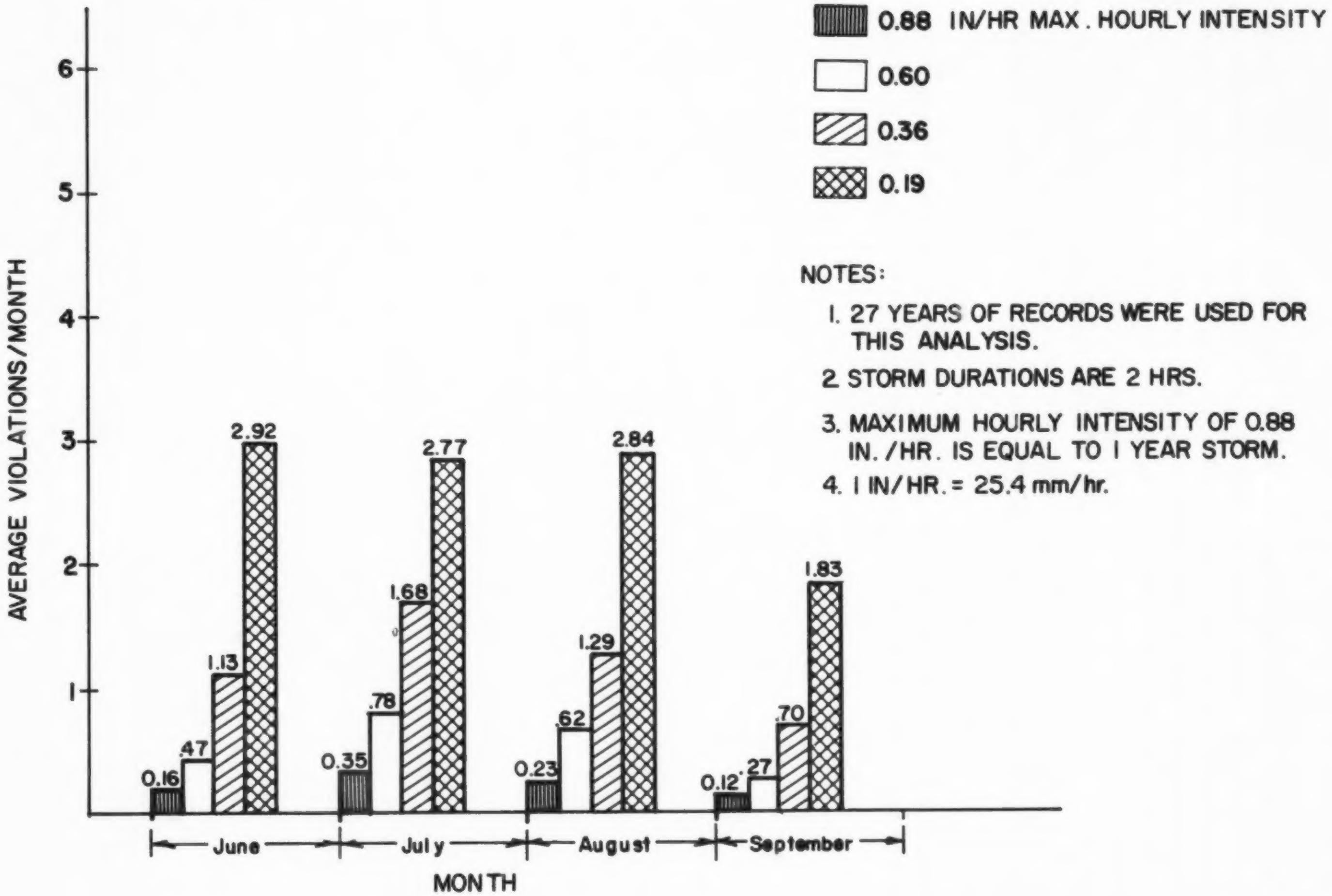


Figure 36. Costs associated with treatment of combined sewer overflows to reduce the frequency of annual water quality violations. (6)

present worth costs (1983) for constructing abatement facilities to treat these storms.

Inspection of the curve presented in Figure 36 shows the "knee" of the curve occurring in the vicinity of $12 million; even with that investment, 13 violations would occur per year. Of the 13 annual violations, over ten will occur during the recreation season from June through September (Figure 37). This case is one where the knee-of-the-curve solution is unacceptable. Since ten violations would essentially prohibit use of the lake for contact recreation, more stringent levels of treatment will ultimately be needed. The selected goal, for which treatment will eventually be provided, is to allow one violation of the contact recreation standard (200 cells/100 ml) per year.

The final CSO abatement plan is presently being developed (6) and is available through the Onondaga County Department of Drainage and Sanitation.



NOTES:

1. 27 YEARS OF RECORDS WERE USED FOR THIS ANALYSIS.
2. STORM DURATIONS ARE 2 HRS.
3. MAXIMUM HOURLY INTENSITY OF 0.88 IN./HR. IS EQUAL TO 1 YEAR STORM.
4. 1 IN/HR. = 25.4 mm/hr.

Figure 37. Average number of violations of fecal coliform standards during the recreation season resulting from treating various intensity storms. Onondaga Lake, New York (6).

REFERENCES

1. Federal Water Pollution Control Act Amendments of 1972, Public Law 92-500. 92nd Cong., 86 Stat. 816, October 18, 1978.

2. Clean Water Act of 1977, Public Law 95-217. 95th Cong., 91 Stat. 1566, October 27, 1977.

3. Shelley, P. E., and G. A. Kirkpatrick. Sewer Flow Measurement, A State-Of-The-Art Assessment. EPA-600/2-75-027, U.S. Environmental Protection Agency, Cincinnati, Ohio, November 1975. 436 pp.

4. Driscoll, E. D. Runnoff and Quality. In: Proceedings of Urban Storm-Water Management Seminars. WPD 03-76-04, U.S. Environmental Protection Agency, Washington, D.C., January 1976.

5. Shelley, P. E., and G. A. Kirkpatrick. An Assessment of Automatic Sewer Flow Samplers. EPA-R2-73-261, U.S. Environmental Protection Agency, Washington, D.C., June 1973. 233 pp.

6. O'Brien & Gere, Inc. Combined Sewer Overflow Abatement Program. Report Prepared for Onondaga County, New York (in preparation).

7. Areawide Assessment Procedures Manual, Volumes I, II and III. EPA-600/9-76-014, U.S. Environmental Protection Agency, Cincinnati, Ohio, July 1976.

8. Manning, M. J., et al. Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges, Volume III: Characterization of Discharges. EPA-600/2-77-064C, U.S. Environmental Protection Agency, Cincinnati, Ohio, August 1977. 290 pp.

9. Report to the Congress by the National Commission on Water Quality. U.S. Government Printing Office, Washington, D.C., March 1976. 90 pp.

10. Report to Congress by the Office of the Comptroller General. Better Data Collection and Planning is Needed to Justify Advanced Waste Treatment Construction. U.S. Government Printing Office, Washington, D.C., December 1976. 70 pp.

11. Geldreich, E. E. Applying Bacteriological Parameters to Recreational Water Quality. J. American Water Works Association, 56: 931, 1975.

12. Oliveri, V. P., et al. Survival of Natural Populations of Salmonella and Indicator Bacteria in Secondary Plant Effluents. Paper presented at the Fiftieth Annual Conference of the Water Pollution Control Federation, Philadelphia, Pennsylvania, October 1977.

13. Geldreich, E. E., and B. A. Kenner. Concepts of Fecal Streptococci in Stream Pollution. J. Water Pollution Control Federation, 41:R336-R352, 1969.

14. Reid, G. K. Ecology of Inland Waters and Estuaries. Reinhold Publishing Corporation, New York, New York, 1961. 375 pp.

15. Huber, W. C., et al. Interim Documentation, November 1977 Release of EPA SWMM, Draft Report. U. S. Environmental Protection Agency, Cincinnati, Ohio, November 1977.

16. Huber, W. C., et al. Storm Water Management Model User's Manual Version II. EPA-670/2-75-017, U. S. Environmental Protection Agency, Cincinnati, Ohio, March 1975. 367 pp.

17. Lager, J. A., et al. Urban Stormwater Management and Technology: Update and Users' Guide. EPA-600/8-77-014, U. S. Environmental Protection Agency, Cincinnati, Ohio, September 1977. 331 pp.

18. Heaney, J. P., and S. J. Nix. Storm Water Management Model: Level I - Comparative Evaluation of Storage-Treatment and Other Management Practices. EPA-600/2-77-083, U. S. Environmental Protection Agency, Cincinnati, Ohio, April 1977. 105 pp.

19. Heaney, J. P., et al. Storm Water Management Model: Level I - Preliminary Screening Procedures. EPA-600/2-76-275, U. S. Environmental Protection Agency, Cincinnati, Ohio, October 1976. 95 pp.

20. Amy, G., et al. Water Quality Management Planning for Urban Runoff. EPA-440/9-75-004, U. S. Environmental Protection Agency, Washington, D. C., December 1974.

21. U. S. Army Corps of Engineers. Storage-Treatment, Overflow, Runoff Model "STORM" User's Manual. Hydrologic Engineering Center, Davis, California, July 1976.

22. Lager, J. A., et al. Development and Application of a Simplified Stormwater Management Model. EPA-600/2-76-218, for U.S. Environmental Protection Agency, Cincinnati, Ohio, August 1976. 153 pp.

23. Brandstetter, A. Assessment of Mathematical Models for Storm and Combined Sewer Management. EPA-600/2-76-175a, U.S. Environmental Protection Agency, Cincinnati, Ohio, August 1976. 530 pp.

24. Chow, V. T., and B. C. Yen. Urban Stormwater Runoff Determination of Volumes and Flowrates. EPA-600/2-76-116, U.S. Environmental Protection Agency, Cincinnati, Ohio, May 1976. 252 pp.

25. U.S. Department of Commerce, Weather Bureau. Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years. Washington, D.C., May 1961.

26. Keifer, C. J., and H. H. Chu. Synthetic Storm Pattern for Drainage Design. J. Hydraulic Division, Proceedings of the American Society of Civil Engineers, 93 (HY4): 1332-1-1332-25. 1957.

27. Marsalek, J. Comparison of Runoff Simulations for Actual and Synthetic Storms. Presented at Storm Water Management Model Users Group Meeting, Milwaukee, Wisconsin, November 3-4, 1977. Sponsored by U.S. Environmental Protection Agency, Washington, D.C. 15 pp.

28. McPherson, M. B. The Design Storm Concept. Presented at Institute of Stormwater Detention Design, University of Wisconsin, April 14, 1977, Madison, Wisconsin. 20 pp.

29. Limno-Tech, Inc. Mathematical Modeling of the Impact of Storms on Water Quality in Onondaga Lake. Prepared for Stearns & Wheler, Civil and Sanitary Engineers, and Onondaga County, New York. Ann Arbor, Michigan, 1978. 133 pp.

30. DiToro, D. M., et al. A Dynamic Model of the Phytoplankton Population in the Sacramento-San Joaquin Delta. In: Nonequilibrium Systems in Natural Water Chemistry, R. F. Gould, ed. Advances in Chemistry Series No. 106, American Chemical Society, 1971. pp. 131-180.

31. Thomann, R. V. Systems Analysis and Water Quality Management, Environmental Research and Applications, Inc., New York, New York, 1972. 286 pp.

32. Canale, R. P., R. L. Patterson, J. J. Gannon, and W. F. Powers. Water Quality Models for Total Coliform Bacteria in Grand Traverse Bay. J. Water Pollution Control Federation, 45:325-336, 1973.

33. Gaden, E. Aeration and Oxygen Transport in Biological Systems. In: Biological Treatment of Sewage and Industrial Wastes, R. F. Gould and W. W. Eckenfelder, eds. Reinhold Publishing Corporation, New York, New York, 1956.

34. Hydroscience, Inc. Water Quality Analysis for the Markland Pool of the Ohio River. Prepared for Malcolm-Pirnie Engineers, Metropolitan Sewer District of Greater Cincinnati, Ohio, 1968.

35. American Public Health Association, et al. Standard Methods for the Examination of Water and Wastewater, Thirteenth Edition, Washington, D.C., 1971. 774 pp.

36. Banks, R. B., and F. F. Herrera. Effect of Wind and Rain on Surface Reaeration. J. Environmental Engineering Division, Proceedings of the American Society of Civil Engineers, 103(EE3): 489-504.

37. Canale, R. P., et al. A Biological Production Model for Grand Traverse. Technical Report No. 37, University of Michigan Sea Grant, Ann Arbor, Michigan, 1974. 116 pp.

38. Chapra, S. C. Total Phosphorus Model for the Great Lakes. J. Environmental Engineering Division. Proceedings of the American Society of Civil Engineers, 103(EE5): 1977. pp. 147-161.

39. Murphy, C. B., and G. J. Welter. Indices of Algal Biomass and Primary Productivity in Onondaga Lake. Presented at National Conference on Environmental Resources Development and Design, ASCE Environmental Engineering Division, Seattle, Washington, 1976.

40. Stearns & Wheler, Civil and Sanitary Engineers. Progress Report: Onondaga Lake Storms Impact Study. Department of Drainage and Sanitation, Onondaga County, New York, 1978. 102 pp.

41. Onondaga County. Onondaga Lake Study. Project No. 11060, FAE 4/71, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1971. 406 pp.

42. Wetzel, R. G. Limnology. W. B. Saunders Publishing Company. Philadelphia, Pennsylvania, 1975.

43. O'Brien & Gere, Inc. Onondaga Lake Monitoring Program. Yearly Report Prepared for Onondaga County, New York. Syracuse, New York, 1970, 1971, 1972, 1973, 1974, 1975.

44. Stearns & Wheler, Civil and Sanitary Engineers. Onondaga Lake Monitoring Program. Yearly Report Prepared for Onondaga County, New York, Cazenovia, New York, 1976, 1977.

45. Great Lakes Institute. Great Lakes Institute Data Record Surveys, Parts I and II. University of Toronto, Canada, 1963.

46. Stearns & Wheler, Civil and Sanitary Engineers. Onondaga Lake Storms Impact Study. Report Being Prepared for O'Brien & Gere, Inc., and Onondaga County. Cazenovia, New York, in preparation.

47. Walker, W. W. Some Analytical Methods Applied to Lake Water Quality. Ph. D. Thesis, Harvard University, Cambridge, Massachusetts, 1977.

48. Pisano, W. C., and C. S. Queiroz. Procedures for Estimating Dry Weather Pollutant Deposition in Sewerage Systems. EPA-600/2-77-120, U. S. Environmental Protection Agency, Washington, D. C., July 1977.

49. Turner, B. G., et al. 1976 Needs Survey. EPA-430/9-76-012, U. S. Environmental Protection Agency, Washington, D. C., February 1977. 400 pp.

50. Sonnen, Michael B. Abatement of Deposition and Scour in Sewers. EPA-600/2-77-212, U. S. Environmental Protection Agency, Washington, D. C., November 1977. pp. 115.